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STUDY AND EVALUATION OF EXISTING TECHNIQUES FOR MEASURING AIRCRAFT WINDSCREEN OPTICAL QUALITY: DEVELOPMENT OF NEW TECHNIQUES FOR MEASURING AIRCRAFT WINDSCREEN OPTICAL DISTORTION.

Technical rept.

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This report has been reviewed by the Office of Public Affairs (PA) and is releasable to the National Technical Information Service (NTIS). At NTIS, it will be available to the general public, including foreign nations.

This technical report has been reviewed and is approved for publication.

FOR THE COMMANDER

CHARLES BATES, JR.
Chief
Human Engineering Division
Air Force Aerospace Medical Research Laboratory

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A program to study and develop techniques for evaluating windscreen optical quality was conducted in support of the Aerospace Medical Research Laboratory's windscreen program. The bird impact resistant transparency (BIRT) windscreens under study were both thick and lightweight laminated components developed to reduce the threat to low-flying aircraft from bird impact. Visual performance is affected by several optical variables of the windscreens; however, this program addressed only the techniques used to evaluate optical distortion. Results of the study indicated that grid board photographic (continued)

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techniques are simple and easy to perform, but errors as large as 20% occur in manual data reduction. Point-by-point measurement of F-111 windscreen optical distortion has shown that this technique provides high accuracy, but is very time consuming. Point-by-point measurements of four representative F-111 windscreens have shown that angular deviations will not usually exceed 40 minutes of arc and that localized optical distortion effects are characterized by large, highly localized variations in angular deviations. Techniques using raster-scanned laser probe beams in conjunction with retro-reflecting screens and holographic lenses could provide the capability for high-speed evaluation of optical distortion in windscreens. The technique to be developed for quantified evaluation of optical distortion should be a grid board photographic system. A grid board digitization system is described to eliminate data reduction errors.

PREFACE

The University of Dayton prepared this report under the terms of Contract F33615-78-C-0501, sponsored by Aerospace Medical Research Laboratory (AMRL), Wright-Patterson Air Force Base, Ohio. Major R. G. Eggleston, Visual Display Systems Branch of the Human Engineering Division, was the AMRL technical monitor of the contract.

J. S. Harris served as the Principal Investigator for the University of Dayton. Other major technical contributions from the University of Dayton to the program were made by K. G. Harding, J. S. Harris, S. H. Mersch, J. S. Marcheski, J. P. Murphy, and R. W. Tait.

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SECTION 1

SUMMARY AND INTRODUCTION

The University of Dayton is conducting a program for the Study, Evaluation, and Development of Techniques for the Evaluation of Windscreen Optical Quality for the Aerospace Medical Research Laboratory.* In this program, the University provides support for a research program on optical evaluation of aircraft windscreens. The studies, experiments, and results reported here describe the program.

The BIRT windscreens under study were both thick and lightweight laminated components developed to reduce the threat to low-flying aircraft from bird impacts. The visual performance of these windscreens is limited by several optical variables; this program addresses only the techniques used to evaluate optical distortion.

1.1 OBJECTIVE

A major objective of the AMRL Windscreen Program is evaluating existing optical test procedures and the development of new test procedures for assessing the optical quality of aircraft windscreens. Studies and experiments were conducted on the techniques now used for evaluation of windscreen optical quality, and two new test techniques were designed and evaluated.

1.2 PRINCIPAL PROGRAM TASKS

The work performed in this program involved five principal tasks:

1. Identification, study, and evaluation of existing techniques used to assess the optical quality of aircraft windscreens.

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*This report was written in 1979 while the contract was still in progress; consequently, the author wrote it in accordance with the ongoing status of the work. No attempt was made to rewrite the report in past tense, although the entire effort by University of Dayton is completed.

2. Experimental study of techniques now used for measurement and evaluation of windscreen optical distortion.

3. Experimental evaluation of the optical distortion in four F-111 windscreens.

4. Development of new techniques for evaluating windscreen optical distortion.

5. Recommendation of the best system for obtaining quantified optical distortion data.

1.3 PRINCIPAL RESULTS

The program has produced the following results, which will be discussed in detail in this report.

1. The optical effects now being evaluated in windscreen optical quality measurements include optical distortion, angular deviation, optical defects, optical transmission, haze, multiple imaging, binocular disparity, and birefringence-produced rainbowing.

2. The study of what techniques should be used for evaluation of windscreen optical quality showed good agreement on the best way to evaluate all the optical effects except optical distortion, birefringence-produced rainbowing, and multiple imaging.

3. Grid board photographic techniques are simple and easy to perform, but errors as large as 20 percent occur in manual data reduction.

4. Point-by-point measurement of F-111 windscreen optical distortion has shown that this technique provides high accuracy, but is very time consuming.

5. Point-by-point measurements of four representative F-111 windscreens have shown that angular deviations will not usually exceed 40 minutes of arc and that

localized optical distortion effects are characterized by large, highly localized variations in angular deviations.

6. New techniques using raster-scanned laser probe beams in conjunction with retro-reflecting screens and holographic lenses could provide the capability for high speed evaluation of windscreen optical distortion.

7. The technique to be developed for quantified evaluation of windscreen optical distortion should be a grid board photographic system. A grid board digitization system is described and proposed to eliminate data reduction errors.

SECTION 2

STUDY OF TECHNIQUES FOR EVALUATION OF WINDSCREEN OPTICAL QUALITY

As part of the Aerospace Medical Research Laboratory's Windscreen Program, the University of Dayton has reviewed the test procedures now used for evaluating windscreen optical quality. The task described in this report involved a review of the literature to identify and evaluate current techniques, and that review will be used to determine what new test procedures are required for evaluation of aircraft windscreens. This report will indicate that, as a result of previous work, most of the required techniques for windscreen optical evaluation have been developed, and a standard method for evaluation has been defined. The most important area of evaluation in which agreement on a technique has not been possible, is that of optical distortion. This study was directed toward the effect of optical distortion, with emphasis on two facts: distortion is one of the most important optical effects on pilot vision, and there is presently no agreement on a single method for quantitative evaluation of distortion.

2.1 OPTICAL EFFECTS IN AIRCRAFT WINDSCREENS

Because of the need for good pilot visibility, the optical quality of aircraft windscreens must be maintained while the stringent requirements imposed by high-speed flight are met. For the best forward vision, the ideal windscreen would be a flat plate installed nearby perpendicular to the pilot's line of sight. Improved aerodynamic performance for high-speed flight has called for windscreens that are inclined at low angles to the horizon and have curved surfaces. The curved windscreens, while providing a larger unobstructed field of view, have introduced undesirable optical effects. The optical quality of the windscreens has also suffered because of the requirement for laminated multilayer windscreens to provide improved strength and shatter resistance. The optical effects produced by the

windscreen involve changes in both the position and magnification of any object observed through the windscreen.

Figures 2.1, 2.2, 2.3, 2.4, and 2.5 show examples of the optical effects produced by aircraft windscreens. Figure 2.1 illustrates the angle of incidence for forward vision. The angle of incidence is the angle between the windscreen normal and the pilot's horizontal line of sight. Observation through a windscreen will result in displacements for observation at angles of incidence not equal to 0° (Figure 2.2), and imperfections in the window due to prismatic errors will result in angular deviation between the true position of the object and its apparent position as observed through the windscreen (Figure 2.3). Localized variations in surface parallelism or prismatic errors will produce variation in the angular deviation errors over the windscreen (Figure 2.4), and variations in angular deviation over the windscreen will produce distortions in objects observed through the windscreen. Attempts to describe the effects of distortion have been categorized by such characteristics as bending, sharp bending, bull's eyes, blurring, convergence, magnification, and rolling.[1,2] The definitions of distortion have been in terms of the rate of change of angular deviation[1,3] and nonuniform rate of change of deviations.[4]

In addition to angular deviation errors produced by nonparellelism of the front and back surface of a windscreen, the curvature required in the windscreens now being designed for high-speed flight also introduced angular deviation errors. This is shown in Figure 2.5, where the angular deviation produced by curvature of the windscreen will vary with the angle of observation as well as with the observer's eye location. Again, the pilot will see distortion over his field of vision.

The angular deviation and distortion observed in Figures 2.3, 2.4, and 2.5 will be apparent from a single eye position. In the operation of an aircraft, a pilot looking through the windscreen will be using two eyes; and any variation in the angular

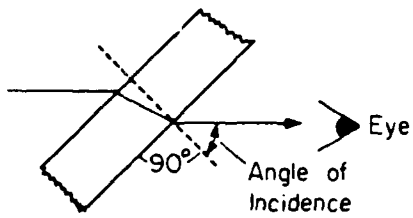


Figure 2.1 Angle of Incidence.

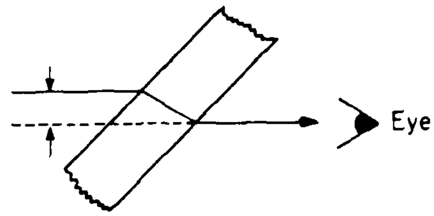


Figure 2.2 Displacement of Ncn-normal Angle of Incidence.

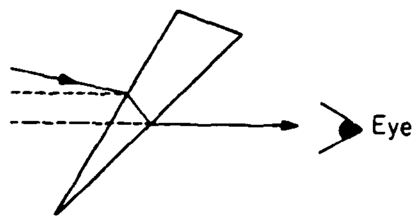


Figure 2.3 Angular Deviation and Displacement Produced by Prismatic (Wedge) Errors.

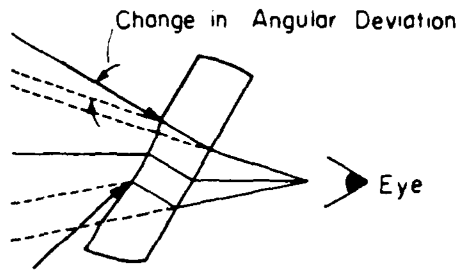


Figure 2.4 Localized Variation in Windscreen Shape Producing Angular Deviation and Displacement.

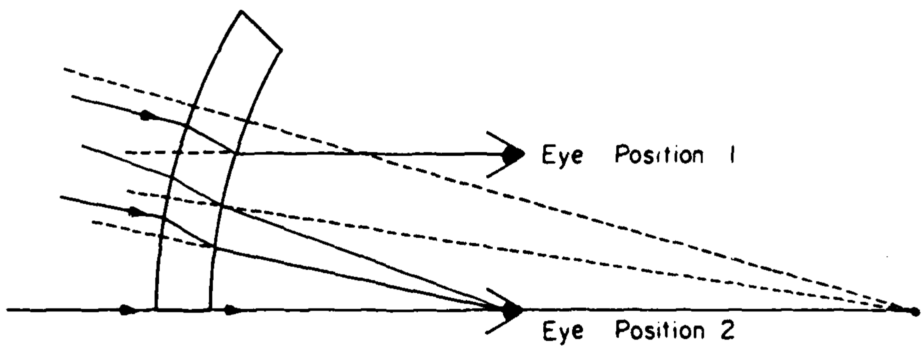


Figure 2.5 Windscreen Curvature Producing Angular Deviation and Displacement.

deviation for an object at infinity for the two eyes will produce double vision. This binocular viewing effect has been called binocular deviation[5,6] and binocular disparity.[7,8] Task[8] has recommended resolving binocular disparity effects into vertical and horizontal components, since the visual sensitivity to vertical and horizontal disparity is markedly different. Corney[6] described how the tolerance to vertical disparity is the most stringent and how the eyes' ability to counteract double vision will keep the images overlapped until the vertical difference in angular distortion exceeds 10 minutes of arc. The British military specification for binocular deviation in windscreens is based on not exceeding the limit of vertical disparity.[9]

The angular deviation errors produced by windscreen prismatic errors and irregularities in the surfaces of the windows will be dependent upon the angle of incidence. As the angle of incidence is increased, the angular deviation will be magnified. Figure 2.6 shows how the angular deviation and its derivative will increase as the angle of incidence is increased from normal incidence to 90°, and in both cases the dependence on angle of incidence starts to increase rapidly after an angle of incidence of 60°.

Although not a psychophysical concept, one of the approaches to defining and evaluating windscreen optical distortion has been in terms of the localized derivative of the angular deviation.[2,3] This is because the optical deviation producing visual distortion comes from a combination of angular deviation errors and lateral deviation errors (displacement) in aircraft windscreens. Changes in this absolute or optical deviation over the pilot's field of view result in distortion, and some evaluators[3] believe the lateral deviation effects are not significant in producing windscreen optical distortion. Because of this analysis on the effects of angle of incidence, military standards[10,11,12,13] have required that the angle of incidence not exceed 60°. However,

recent Air Force aircraft windscreens have not been designed within these specifications. The F-106, F-111, B-1, T-28, F-5, and F-15[1] have all exceeded these requirements, and sacrificing pilot visual performance has been justified by the increased aerodynamic performance of the aircraft.

In addition to the effects of angle of incidence, any windscreen curvature will affect angular deviation, as shown in Figure 2.4. A curved windscreen will produce angular deviation for angles of incidence not equal to zero, even where there are no windscreen defects and the eye position is not at the windscreen center of curvature. The amount of angular deviation depends upon the radius of curvature, windscreen thickness, and the windscreen's index of refraction. A plot[14] showing the variation of angular deviation in the rate of windscreen thickness/radius for angles of incidence of 30°, 45°, and 60° is shown in Figure 2.7.

In addition to the displacement and angular deviation optical effects in aircraft windscreens, windscreen optical effects are produced by windscreen reflection and scatter. Windscreen reflections produce two undesirable effects, as shown by Figure 2.8. The first is that light sources within the aircraft can be reflected by the windscreen into the pilot's eyes, obscuring vision as shown in Figure 2.8a. This effect is especially objectionable in night flying. The percent of light reflected by the inside and outside surfaces of the windscreen varies from 4 percent at zero angle of incidence to 100 percent as the angle of incidence approaches 90°. In addition to the reflection of light from internal sources, light from objects exterior to the aircraft will be reflected from the front and back surfaces of the windscreen. For angles of incidence at other than zero degrees, the reflections inside the windscreen can produce secondary multiple images, as shown in Figure 2.8b. These multiple images can also occur for the internal reflection problem of Figure 2.8a. For a laminated windscreen there will be

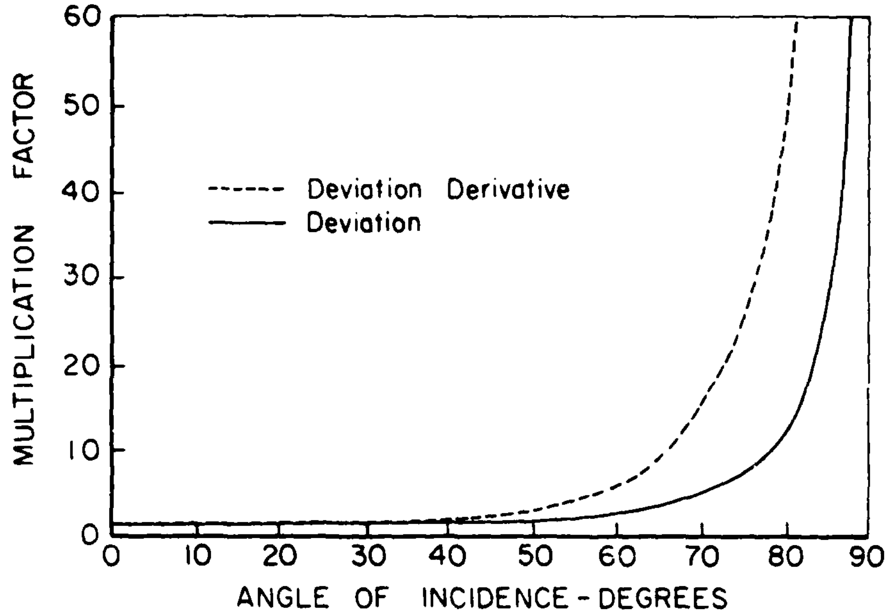


Figure 2.6. Effects of Angle of Incidence on Optical Deviation (From AFSC Design Handbook 2-1, 1969) and Its Derivative. From J. C. Cocagne and J. C. Blome, Optical Requirements For High Performance Aircraft Glass, 1968.

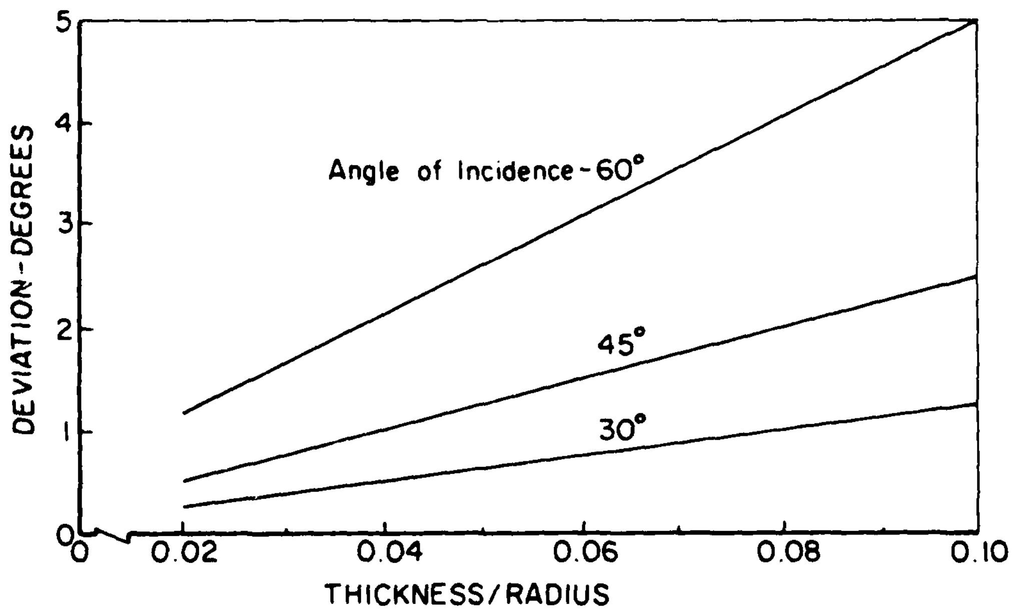


Figure 2.7. Effects of Thickness/Curvature Ratio on Angular Deviation at Three Angles of Incidence. From R. A. Holloway, Survey Of Test Procedures For Aircraft Transparencies, 1970.

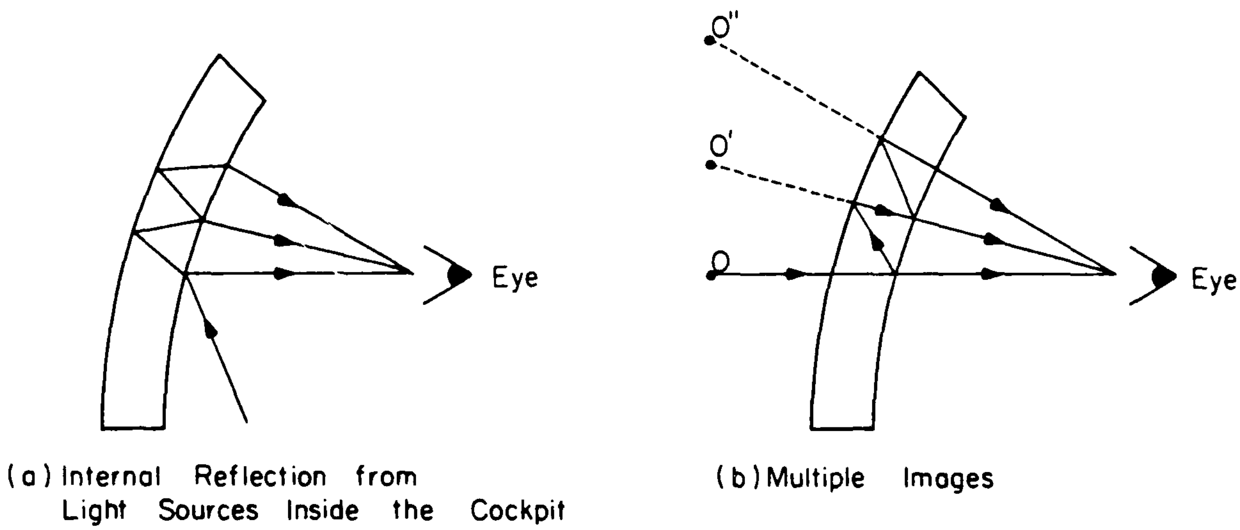


Figure 2.8. Windscreen Optical Reflection Effects.

additional reflection effects; but because of the lower index differences within a windscreen, these are less intense than the multiple images produced by reflection at the front and back surfaces. Again, these multiple images are usually a problem only for night flying.

The last two optical effects usually measured in windscreen evaluation are haze and transmission. Haze is defined in terms of the light scattered during passage through the windscreen. Haze contributes to glare when looking at bright light sources and reduces the contrast in the pilot's field of view. In practice windscreen surface quality is the most significant factor in producing windscreen haze. Transmission losses in the windscreens are produced by absorption within the windscreen, absorption in windscreen coatings, reflection losses, and scattering. The most significant effect in reducing the windscreen transmission is the loss produced by surface reflections. Figures 2.9 and 2.10[15] show how the reflection losses of a beam from the outside of the windscreen front surface or internally from the front or back surfaces of a dielectric, such as glass or plastic, will vary with the angle of incidence and polarization. These losses can be quite large for angles of incidence beyond 70° for external reflections or beyond 40° for internal reflection. In conjunction with the measurement of haze and transmission for windscreens, the material color as well as the windscreens' surface scratches and inclusions are evaluated.

For laminated windscreens developed to provide greater strength and to reduce the threat posed by bird impacts to low-flying aircraft, the effect of birefringence must be evaluated. The polycarbonate materials[16] used for the internal layers in these windscreens are birefringent, and during the windscreen fabrication process variations in birefringence develop over the windscreen. Because the windscreen's front and back surfaces act like partial polarizers for non-normal incidence and the windscreen contains birefringent material, the transmission of unpolarized or partially polarized white light will be wavelength

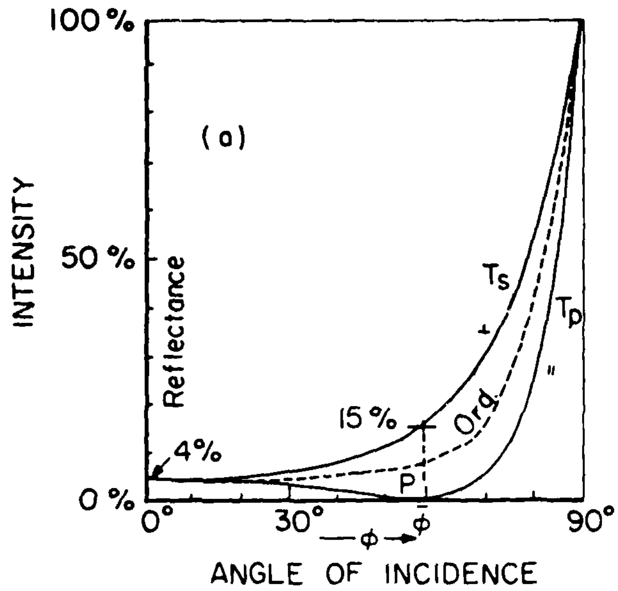


Figure 2.9. Reflectance for a Dielectric Having n = 1.5. From F. A. Jenkins and H. E. White, Fundamentals of Optics (McGraw-Hill Book Company, Inc., New York), 1957.

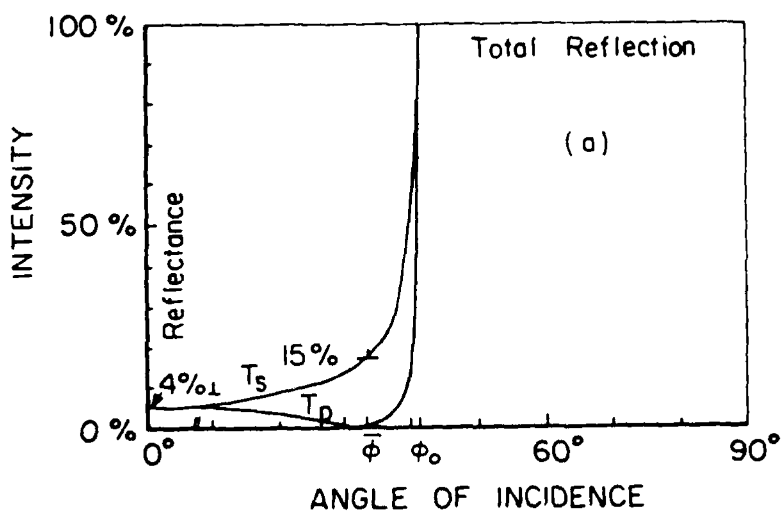


Figure 2.10. Internal Reflectance for a Dielectric Having $n = 1.5$. From Jenkins and White, 1957.

dependent. The color effects associated with windscreen birefringence can degrade visual performance and must be minimized during the windscreen fabrication process[16].

2.2 REQUIREMENTS FOR EVALUATION OF WINDSCREEN OPTICAL QUALITY

The purpose of this review task was to search the literature to identify the techniques now used to assess the optical quality of aircraft windscreens. The emphasis was to be directed toward evaluation of techniques used to measure optical distortion. The reason for this emphasis is the lack of agreement on requirements for optical distortion.

2.2.1 Survey of Present Requirements

In 1973 Grether[1] summarized the existing requirements of US military aircraft for optical effects or parameters, and these are shown in Table 2.1. Windscreens are classified into Type I, bullet resistant, general purpose, and Type II, bullet resistant for use with reflector-type gunsights. Each type is further classified into Grades A, general purpose, and B, high light transmission. The standards of Table 2.1 for deviation, transmission, and haze are given for zero degree angle of incidence. To determine what these values would be at the installed angle, the multiplication factors of Figures 2.6, 2.9, and 2.10 can be applied.

All the optical effects shown in Table 2.1 are covered by military specifications, except distortion. The distortion specifications from the Air Force Design Handbook[10] are reported, but the actual specification is left to the procuring agency. The standards do not cover the birefringence effects associated with laminated aircraft windscreens, multiple imaging, windscreen surface scratches and inclusions, binocular deviation, and windscreen material color.

Corney[5,6] in Great Britain has been actively involved in determining optical requirements for aircraft windscreens. This

TABLE 2.1. OPTICAL ACCEPTANCE STANDARDS FOR TRANSPARENCIES OF U.S. MILITARY AIRCRAFT

Optical Parameter	Standards	Source
Angle of Incidence	60° maximum throughout windshield	AFSC-DH-2-1 DN 3A1, 1969
	60° maximum in any part used for approach and landing	MIL-W 81752 (AS) 1970
	60° maximum at horizontal vision line	MIL-STD-850B 1970
Radius of Curvature Type II, A & B	Flat, minimum radius 500 ft	MIL-G-5485C, 1971
Deviation at 0° angle of incidence Type I Type II	 3 min. maximum 31.5 sec. maximum	MIL-G-5485C
Deviation at installed angle, in gunsight area	1.8 min. maximum	AFSC-DH-2-1 DN-3A1, 1969
Transmission at 0° angle of incidence Grade A	Range from 81% for 1/2 in. to 71.6% for 3 in. thickness	MIL-G-5485C
Grade B	Range from 85% for 1/2 in. to 78% for 3 in. thickness	MIL-G-5485C
Distortion	To be specified by procuring agency	MIL-G-5485C & MIL-G-25667B
	Deviation change per inch of surface at installed angle, for Optically flat 1.0 min/in. Flat 2.5 min/in. Single Curved 4.0 min/in. Compound 5.0 min/in.	AFSC-DH-2-1 1969
Haze, at 0° angle of incidence	1% up to 5/8 in. thickness 1.5% for 5/8" to 1-1/4 in. thickness	MIL-G-25667B, 1970

work[6] has led to development of requirements for five types or categories of windscreens, and these are summarized in Table 2.2. If the difference in installed angle is taken into account, the requirements of Grether and Corney (Category I) show fair agreement. Corney also provides information on requirements for binocular deviation, surface scratches and inclusions, and visual distortion.

None of these studies developed requirements for windscreen coloring or birefringence. As in the case of distortion, these requirements have not been standardized and are left up to the individual programs for specification.

2.2.2 Requirements for the F-111 and F-16

As a result of reviewing the literature on development of requirements, we found that except for color, birefringence, multiple imaging, and distortion, general agreement was reached on acceptable levels of windscreen optical effects. For the purposes of this study, the best way to show this is to consider specific examples. Presently, two windscreen programs are undergoing research and evaluation by the Aero Medical Research Laboratory for the F-111 and F-16. The F-111 is a V-type two-panel windscreen, and the F-16 is a one-panel windscreen. These windscreens represent different types of problems because the F-111 is a large aircraft with side-by-side pilot and copilot, while the F-16 is a smaller aircraft with a narrow long transparency and only a single forward design eye position (F-16A), or an extended windscreen for a front and back seating arrangement for pilot and copilot (F-16B). The F-111 also uses separate canopies in addition to the windscreen.

The optical requirements for the F-16[17] windscreen include the following:

1. angular deviation
2. optical distortion
3. optical defects, i.e., scratches, blemishes, and bubbles

Table 2.2. ACCEPTABLE LIMITS OF THE PARAMETERS ASSOCIATED WITH VISION THROUGH OPTICAL TRANSPARENCIES

PARAMETER	CATEGORY I	CATEGORY II	CATEGORY III	CATEGORY IV	CATEGORY V
In-Line visual light transmission In horizontal plane In area of lowest transmission	Not less then 60% Not less than 40%	Not less than 70% Not less than 50%	Not less than 55% Not less than 40%	As Category III	As Category III
Visual Distortion -as asssssed by divergence of adjacent grid lines by method C	Requirement covered by other	Not greater than 1 in 25	Not greater than 1 in 20	Not greater than 1 in 10	Not greater than 1 in 5
Binocular Deviation	Not more than 10 minutes	As Category I, also not to exceed 2.5 minutes in vertical direction	As Category I	As Category I	Not specified
Visible inclusions, seeds,* hairs, fibres and scratches	Allow 1 Type A defect only within any circular area of 100 mm radius No Type B defects No Type C defects	a) Allow 1 Type B defect and 4 Type A defects within any area of 150 mm radius b) Allow 8 Type A defects only within the same area No Type C defects	As Category II	a) Allow 1 Type C defect and 4 Type A defects within any area of 150 mm radius b) Allow 2 Type C and 8 Type A defects in the same area	As Category IV
Type of Transparency	Forward-facing windscreen of the highest quality suitable for weapon aiming	Forward-facing side panels for reconnaissance and search	Main vision area of forward-facing panels other than those in Categories I and II; defined areas of side panels or quarter lights	Side panels or other nonforward-facing transparencies for all aircraft other than reconnaissance and search, selected areas of canopies	Cabin windows, defined areas of canopies

*NOTES TO TABLE 2.2

Type A defects having a diameter in the range 0.2 - 0.5 mm or equivalent area (0.03 - 0.2 mm^2); this includes hairs, fibres, or hair scratches of width not exceeding 0.1 mm and equivalent area 0.2 mm^2.

Type B defects having a diameter 0.5 - 1.0 mm or equivalent area (0.2 - 0.8 mm^2) including hairs, etc. of widtn not exceeding 0.2 mm and equivalent area 0.8 mm^2.

Type C defects having a diameter 1.0 - 1.5 mm or equivalent area (0.8 - 1.8 mm^2) including hairs, etc. of width not exceeding 0.2 mm and equivalent area 1.8 mm^2.

Defects larger than Type C not admissible.

The following overriding conditions are to be observed.

Defects which are dense black or of other strong color, and strongly reflecting defects (known as "glint") are not admissible in panels of Category I, areas for weapon aiming, but are admissible in other Category I areas, and in Category II and III areas. Similar black Type B defects are not admissible in Category II and III areas.

A local accumulation of defects of dimensions smaller than Type A is admissible provided the haze requirement is met. The haze measurement should then be confined to the area of accumulation.

4. optical transmission
5. haze
6. material specifications, i.e., color

The angular deviation is controlled only in the forward gun-sight area of the windscreen, located in Zone 1 of Figure 2.11. The specification on errors in deviation produced by windscreen defects is that they must be less than ±5 mrad.

For evaluation of minor optical defects the F-16 windscreen is subdivided into three zones as shown in Figure 2.11. The defects must be less than 0.035 inch in length, diameter, or depth; and there cannot be more than 20 in any one zone. The optical defects include imbedded particles, blemishes, bubbles, and scratches.

For evaluation of optical distortion, the windscreen is sub-divided into two areas. Quantitative requirements are based on grid board evaluation, and line slopes must be less than 1 in 11 for Zone I and 1 in 9 for Zones II and III.

Visual examination is made for apparent bending, blurring, divergence, convergence, or jumping of grid lines. Any severe effect would be evaluated by Air Force personnel to determine acceptance or rejection of any questionable windscreen.

The optical transmission of the windscreen must be greater than 79 percent and is measured for normal incidence.

The percent of haze of the above transmitted beams must not be greater than 4 percent.

The color of the material in the laminated windscreen can not exceed a yellowness index of 8.5 for a thickness of 0.25 inch (ASTM-D 1925-70)[18].

The optical requirement for the F-111[19] windscreens include the following:

1. optical distortion
2. birefringence

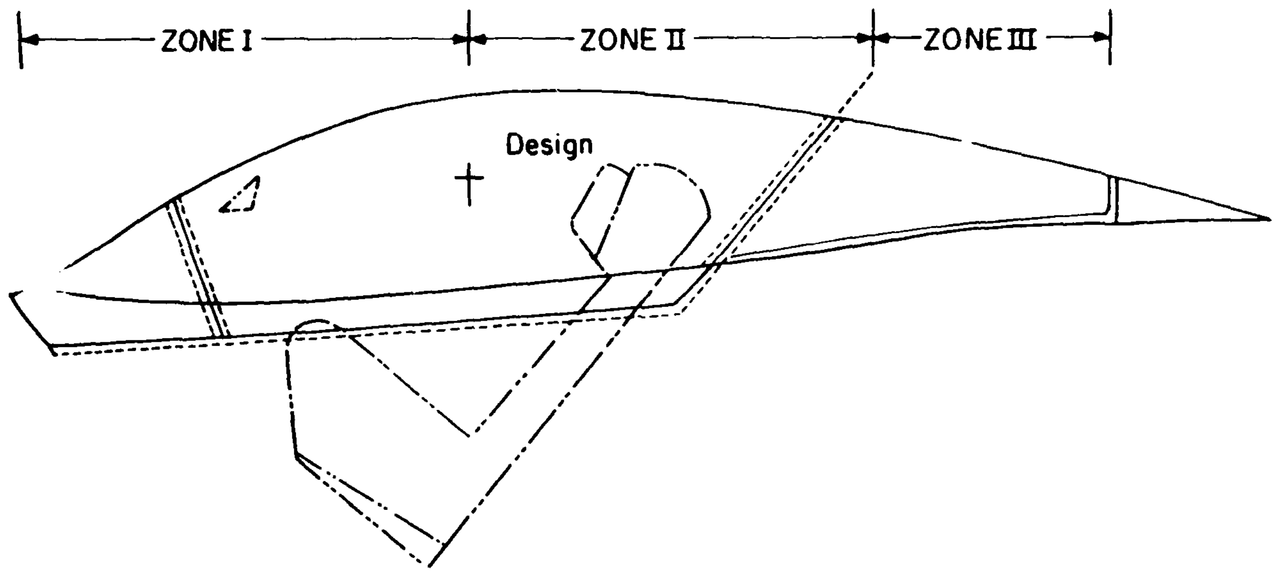


Figure 2.11. Windscreen Evaluation Geometry for F-16.

3. multiple imaging
4. angular deviation
5. haze
6. optical transmission
7. minor optical defects

The F-111 canopies, because of their reduced optical requirements, are evaluated only for optical distortion, haze, and optical transmission. Except for optical distortion, the requirements for the canopies are the same as those for the windshields.

As with the F-16, the F-111 windscreens are required to pass both visual and quantitative tests in evaluation of optical effects. The testing is further complicated for the F-111 because of different types of quantitative specifications for the windscreens and the canopies. The quantitative tests for the windscreens are in terms of lens factor and displacement grade, while the canopies are evaluated in terms of grid line slope. For the windscreen, the lens factor cannot exceed 1.25; and the displace-ment grade shall not exceed 150. These requirements do not apply to the edges of the windscreens. For the canopies, the optical distortion must be limited to that which causes a grid line slope of 1 in 10 in one area and 1 in 6 in the remainder of the canopy. Again these requirements do not apply to border areas.

Visual evaluation of the optical distortion is also required for the windscreens. A grid board is viewed through the windscreen; and severe bending, broken grid lines, sharp bending, blurring, or objectionable bulls' eyes will cause rejection. The Air Force will be responsible for selecting sample windscreens showing acceptable defects.

Visual evaluation is also used to check for optical defects, birefringence produced rainbowing, and multiple imaging. Table 2.3 shows the specification and requirements for the six optical defects to be evaluated. The visual inspection is made from the design eye position.

TABLE 2.3. CLASSIFICATION OF OPTICAL DEFECTS FOR WINDSCREENS

TYPE DEFECT	MAXIMUM SIZE ALLOWABLE	REQUIREMENTS
Scratches	0.020 inch width, 0.010 inch depth, or 3 inch length	Each panel shall be individually evaluated. When the total number and grouping of these types of defects cause a distraction to vision or vision impairment, the panel shall be rejected.
Lint or Hair	3 inch in length	
Smears & Rubs	5/8 inch width or 1-1/2 inch length	
Translucent Inclusions or Imbedded Particles	0.125 square inch in area	The total number of these types of defects between 0.35 and 0.125 square inch in area for translucent defects or between 0.035 and 0.070 square inch in area for opaque defects shall not exceed twelve (12) per panel. Defects up to 0.35 square inch in area shall be acceptable provided they do not cause vision impairment.
Opaque Imbedded Particles & Inclusions	0.070 square inch in area	
Delaminated Area	a) Outboard Acrylic Edge: Maximum 1/8 inch penetration around entire periphery. b) Inboard Acrylic Edge: Maximum 1/4 inch penetration around entire periphery	a) Outboard Acrylic Edge: Individual occurrences are limited to one per edge with a maximum penetration of 1/4 inch inch and maximum length of 3/4 inch.

The visual evaluation of the windscreens for birefringence-produced rainbowing is based upon a comparison with referee windscreen. The Air Force is responsible for selecting a windscreen that shows an acceptable level of rainbowing.

In an acceptable windscreen, multiple imaging must not produce a secondary image that is displaced over three inches with respect to the primary image. This specification is an area weighted evaluation in that this effect must be present over large portions of the pilot's field of view in order to cause rejection. The Air Force will be responsible for reviewing any questionable windscreen.

The allowable haze produced by transmission through the windscreens and samples is specified at normal incidence. For a windscreen without radar reflective coatings, the average value cannot exceed 3 percent; and with the coatings, the haze average value cannot exceed 4 percent.

The average luminous transmittance of the windscreens and canopies is specified at normal incidence. Without the radar reflection coatings, the average transmittance shall be greater than 77 percent; and with the coatings it shall be greater than 70 percent.

The angular deviation for the left and right windscreens is specified and requires evaluation for 135 square grids. The grids (Figure 2.12) are determined by the intersection of a 3 by 3 inch square grid with the windscreens. The angular deviation measurements are referenced to a normal incidence measurement of angular deviation at only one point on the windscreen. The actual magnitude of the specification is difficult to determine because of the way in which it is stated. The windscreen is subdivided into an Area IV with a specification on only deviations of magnitude greater than 3 minutes and Areas I, II, III (Figure 2.13), which are required to fall within a circle of 20 minutes' deviation and with a certain prescribed direction. Specifying the angular deviation

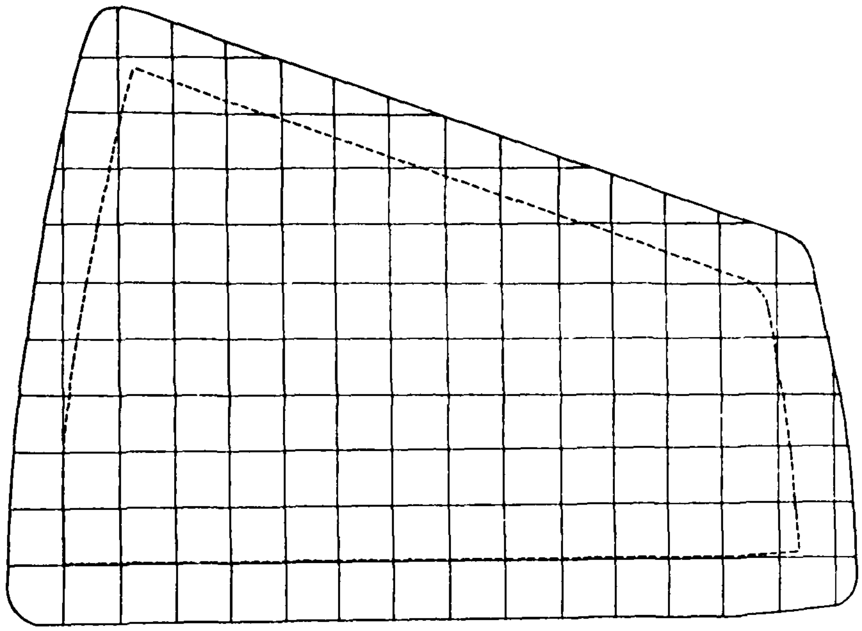


Figure 2.12. Windscreen Grid for Evaluation of Angular Deviation for the F-111 Windscreens.

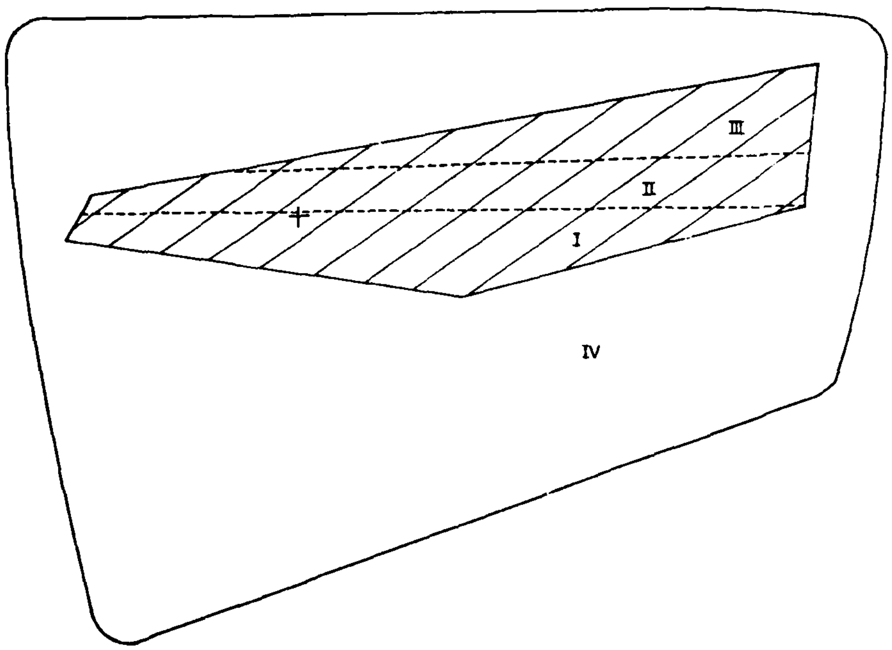


Figure 2.13. Four Zones for Evaluation of Angular Deviation for the F-111 Windscreens.

where the angle of incidence varies with each measurement, makes it difficult to determine the actual angular deviation specification, and the value of deviation allowed is not mentioned in the acceptance test procedures. Within Area IV, the direction of all deviations greater than 3 minutes must be evaluated. The vectors are required to have less than 180° difference in angular direction over any 18 inch horizontal section of the windscreen.

2.3 TECHNIQUES FOR EVALUATION OF WINDSCREEN OPTICAL QUALITY IN THE F-16 AND F-111

Table 2.4 shows the optical effects or parameters that are measured for the F-111 and F-16 evaluation. The requirements for these parameters were discussed in the previous section, and the techniques used for their evaluation are described in this section. The current test procedures for evaluating the F/FB-111 are given in the "Acceptance Test Procedure 601-E, Revision E for F/FB-111 Bird Impact Resistant Transparencies"[19] and the procedures for the F-16 are given in "Secification No. 16ZK002D, Critical Item Development Specification F-16 Transparencies."[17]

TABLE 2.4. OPTICAL EFFECTS EVALUATED FOR F-111 AND F-16

Measured Parameter	F-111	F-16
Optical Distortion	YES	YES
Angular Deviation	YES	YES
Optical Defects	YES	YES
Optical Transmission (luminous, transmittance)	YES	YES
Haze	YES	YES
Birefringence-Produced Rainbowing	YES	NO
Multiple Imaging	YES	NO
Binocular Disparity	NO (Documented Only)	NO

2.3.1 Optical Distortion

The optical distortion of the F-16 is evaluated by visual and photographic evaluation of a grid board from the design eye position. The grid board has white lines against a black background. The maximum spacing of the white lines is one inch, and the grid board is located 15 feet from the transparency under test. To obtain qualitative data, the procedure is to photograph the grid board through the transparency and then to measure the grid line slopes. The slopes are measured from 8-1/4 by 10-inch photographs using a drafting board. The camera used, a Speed-Graphics 4X5 with 135 mm lens or the equivalent, is mounted at the forward design eye position. For the F-16B windscreen, the optical distortion is also evaluated from the rear design eye position.

Visual evaluation of the optical distortion requires only that the grid board, when observed through the windscreen from the design eye position, indicate no immediate apparent bending, blurring, divergence, convergence, or jumping of grid lines. Any visually observed defect that may be severe enough for rejection is to be photographed and reviewed by the Air Force.

Optical distortion of the F-111 windscreen is evaluated with several techniques. Visual techniques are used for evaluation of the windscreen, and different quantitative techniques are used for evaluation of the windscreens and canopies. Quantitative evaluation of the windscreens is obtained from measurement of lens factor and displacement grade, and canopy quantitative evaluation is obtained by the grid line slope technique. There is no visual optical distortion evaluation of the canopy.

The windshield visual optical distortion evaluation is performed by evaluation of grid board distortion from the design eye position. The grid board is a one inch square grid of white lines on a black background and is large enough to cover the field of view through the windscreen. The grid board is located 16.67

feet from the design eye position. Distortion is judged by comparison to a referee windscreen selected by the Air Force. A magnitude estimation procedure is used to rate the referee windscreen and permit visual evaluation of the production windscreens.

The lens factor and displacement grade determination measurements used for quantitative evaluation of the windscreen are obtained from 8 by 10 inch photographs of the grid board, taken at the design eye position using a 4 x 5 view camera with a 135 mm lens. The photographs must be properly positioned on a drafting board to allow accurate, orthogonal measurements. Measurements must be made on a section of the grid board that extends beyond the limits of the transparency. Evaluation of the grid board beyond the transparency gives a true measure of grid squares per inch. To determine the lens factor, measurements are made of the squares per inch as seen through the windscreen. The grid images are compared to determine the ratio of squares per inch outside the windscreen divided by the squares per inch as photographed through the windscreen. This ratio (usually greater than one) is then cubed to obtain the "lens factor." The displacement grade is determined from measurements of the maximum displacement of the horizontal and vertical grids relative to their position without the displacement produced by imaging through the windscreen. Again the grid board image outside the transparency is used as a reference base. The calculations to obtain the displacement grade are not directly translatable to standard values.

The grid line slope evaluation procedure for quantitative evaluation of the canopies is almost identical to the distortion test specified for the F-16. The procedure is to photograph the grid board through the canopy and then to measure the greatest grid line slopes. The measurement is again made using a drafting board. The canopy is mounted ten feet from the grid board with the one-inch square grid pattern, and the camera is mounted at

the design eye position. The slope of the line is specified in terms of the number of grid squares crossed in the direction of the grid line being evaluated.

2.3.2 Angular Deviation

For both the F-111 and F-16, no specific technique is described for measuring angular deviation. It would appear that in both cases so much information is required for acceptance testing that no single technique can be recommended.

In the case of the F-16, the data are taken at the design eye position and four other positions above and below the design eye position. For each position the deviation is measured at 56 positions over the field of view. This is repeated for the rear design eye position of the F-16B. From the measured deviation data, the azimuth and elevation components of the deviation data are plotted and compared to the theoretical deviation. The theoretical deviations are obtained from the following equation.

$$Y_e = C_1 + C_2 [\cos (C_2 E + C_4)], \qquad (1)$$

where Y_e is the elevation component of the angular deviation; E is the elevation view angle in degrees and C_1, C_2, C_3, C_4 are constants for each type of windshield; also,

$$Y_a = 0.2605 + 0.3674A \qquad (2)$$

where Y_a is the azimuth component of the angular deviation, and A is the azimuth view angle in degrees. Angular deviation data are recorded for seven field angles from the gun camera position, which is located 4 inches below and 24 inches forward of the design eye position. From this data an optic data package is prepared showing all the measured experimental angular deviation data, plots of theoretical angular deviation data for the six different positions over the field of view, and curves that compare experimental and theoretical angular deviation data.

For the mapping of the angular deviation at 135 points over each of the right and left windscreens of the F-111, no specific technique is given in the F-111 test procedure.[19] However, two

recommended measurement techniques are diagrammed in the report. The actual test to be used is at the discretion of the manufacturer, so long as the test yields the required data. One technique described evaluates the deviation errors by determining the deviation of an unexpanded laser beam by the test windscreens. The position of the laser beam is plotted on an x-ray recorder, and a complete deviation map is made from the 135 separate measurements. The report outlines the mapping process, and the test specification is long and complicated. The mapping procedure requires the use of three templates which must be aligned according to the direction and magnitude of the "bore sight vector" associated with the point being tested. Each deviation measured is graphically drawn using a vector representation. All the deviation vectors must fall within the tolerance template associated with that area of the windscreen.

2.3.3 Optical Defects

For both the F-111 and F-16, optical defects are evaluated by visual examination. Inspection is performed where the windscreen is between the source and the observer. The illumination source is angularly offset so that the windscreen can be inspected against a dark background. For the F-111 the source specified is blue-white fluorescent lamps; for the F-16 the source specified is the equivalent of light from a clear sky without sun [CIE Illuminant C]. Quantitative measurements are made using an optical comparator. Inspection is made from close in and from the design eye positions.

2.3.4 Luminous Transmittance and Haze

For the F-111 and F-16 the luminous transmittance and haze are determined using the Federal Test Method 3022 of FTM-406 or an equivalent test such as described by ASTM-D 1003-61.[20] By means of a CIE Illuminant C source, the haze and transmittance are determined by measuring the light illuminating the windscreen, T_1; the total light transmitted by the windscreen, T_2; the light

scattered by the measuring instrument, T_3; and the light scattered by the instrument and windscreen, T_4. From the measured values the luminous transmittance T_t, is given by

$$T_t = \frac{T_2}{T_1} \qquad (3)$$

To calculate the amount of haze, the diffuse transmittance, T_d, is first calculated from

$$T_d = [T_4 - T_3 (T_2/T_1)]/T_1; \qquad (4)$$

and the percentage of haze is obtained from the ratio of diffuse transmittance to luminous transmittance, i.e.,

$$\text{Haze, percent} = \frac{Td}{Tt} \times 100 \qquad (5)$$

2.3.5 Birefringence-Produced Rainbowing

The rainbowing produced by transmission of polarized light through laminated windscreens is evaluated visually for the F-111. This effect is not evaluated for F-111 canopies. There is no specification on birefringence-produced rainbowing for the F-16.

Evaluation of the rainbowing is made with respect to a referee windshield. A light box having a lighted aperture of at least six by nine feet is used to back-illuminate a polarized screen. The light box provides an illumination with at least 300 footlamberts. The illumination must be a diffuse white light source that is 80 percent polarized in the horizontal direction after passage through the polarizing screen. The windshield to be tested is located side by side with the referee windscreen; and both windscreens are placed in the installed orientation, less than one meter from the test pattern. The rainbowing is observed from the design eye position. The evaluator will alternately view the referee windscreen and the inspection windscreen.

Undesirable rainbowing effects will include edged color changes or bright, compact color patterns. The referee windscreen is selected by the Air Force, and a magnitude estimation procedure[19] is used to rate the referee windscreen and to permit visual evaluation of the inspection windscreen.

2.3.6 Multiple Imaging

The multiple imaging effects produced by multiple reflections in the aircraft windscreens are evaluated visually for the F-111. There is no specification on multiple imaging for either the F-16 windscreen or the F-111 canopy.

As in the case of "rainbowing," this evaluation is made with respect to a referee windscreen. The inspection occurs from the design eye position, and a backlighted 6 by 6 inch grid of 1/16 inch wide lines is used as a test pattern. The test pattern must be at least 11 feet high by 16 feet wide, and the back illumination of the test pattern must be at least 300 footlamberts. Again the referee windscreen is selected by the Air Force, and a magnitude estimation procedure [19] is used to rate the referee windscreen and to permit visual evaluation of the inspection windscreen. The windshields are placed in the design installed orientation with the design eye position 200 inches from the test pattern. The referee and inspection windscreens are placed side by side, and the inspector alternately views the referee and inspection windscreen.

2.3.7 Binocular Disparity

There is no specification on the allowed binocular disparity for either the F-111 or F-16. However, for the F-111 a photographic record of the grid board used for evaluation of the optical distortion in the windshields is made with the windscreen 1-3/8 inches to the left and right of the position used in the optical distortion test. The two exposures are done with a red and green filter, and both are recorded on a single sheet of Kodacolor film.

2.4 OPTICAL DISTORTION TESTING TECHNIQUES EVALUATION AND SUMMARY

The major objective of this phase of the evaluation and development of optical test procedures used in aircraft windscreens was to identify and evaluate the techniques used for measuring optical distortion. This section will review these techniques. Although not exhaustive, the techniques evaluated here are representative of all those found in our literature review. Each technique is described, and the evaluation of each approach includes consideration of the following: (1) whether it evaluates lateral deviation, angular deviation, or coupled angular and lateral deviation; (2) whether it evaluates the variation in deviation over the transparency or only maximum and minimum measures of the deviation over the transparency; (3) whether it evaluates binocular disparity effects for transparency deviation effects; (4) whether it evaluates any psychophysical effects; (5) the complexity of any instrumentation required; (6) relative cost of the instrumentation associated with the different techniques; (7) the time required to analyze the experimental data; (8) the level of experience required to perform the test and data analysis; and (9) the accuracy of the data obtained with each technique.

The absence of agreement on a standard for evaluation of optical distortion has arisen because of the various effects associated with its presence. Optical distortion is the localized and overall variations in the image apart from the true image, and is caused by variations in thickness, wedge, or curvature of an optical windscreen. The rays of light traveling through such a windscreen are bent or deviated, both angularly and laterally, and to different degrees. These variations of deviations with changing line of sight can have severe effects on the appearance of objects viewed through the transparency. The resulting image can (1) be bent out of shape; (2) appear magnified or demagnified due to optical power in the windscreen (lensing); (3) be magnified or demagnified in only one dimension, as well as be

shifted in space, due to unequal curvatures of the transparency (anamorphic distortion); and (4) have small localized distortions such as localized power errors (bull's eyes) or symmetrically connected smaller areas (butterflies) due to irreg-ularities or discontinuities in coatings on the transparency.[14]

The effect of distortion of an image is primarily psychological; therefore, the precise accuracy of measuring distortion is difficult to specify. A localized distortion may appear less of a problem than a widespread distortion, since the mind can easily correct for a localized discrepancy. A widespread distortion will warp an image without presenting a known reference of what the object should look like or where it should be located. Therefore, a widespread distortion may give "false" information about the object being viewed. However, a sharp localized distortion may cause an image to jump or change in shape or size very quickly as the image traverses the field of view. This could be very disturbing and confusing, especially in a situation requiring a quick decision. It is clear that all distortion tests must ultimately relate to human factors. However, straightforward visual inspection requires experienced personnel and is very subjective.

To determine how an image is being degraded by optical distortion, any test method must evaluate the extent to which the light rays from a test object passing through the test transparency are deviated in the final image plane, and must map the deviation of the various rays from their paths for a "perfect" image. Two techniques are reviewed here. The first requires the direct measurement of the deviation point by point over the field of view while the second evaluates distortion by a single photographic recording of a grid board that covers the field of view. Of the optical distortion evaluation techniques reviewed, only one directly considered psychophysical effects on vision; and this involved the use of a trained observer.

2.4.1 Beam Deviation: Angular and Lateral

Beam deviation is measured by a number of simple and straightforward techniques. If only angular deviation is to be determined, the windscreen is adjusted so that the evaluation beam is incident normal to the windscreen. By evaluating beam deviation with the windscreen mounted in the design position, the beam deviation over the field of view will include both lateral and angular deviation errors. By the proper experimental techniques, the two deviation effects can be separated and only angular deviation measured if desired.

The American Standard Safety Code 261-1938[21] (MIL-G-5485C,[22] MIL-G-25667B[23]) described a technique whereby a projector is used to project a straight line between two straight lines on a screen 25 feet away. The windscreen or test sample is then placed one foot from the projector, between the projector and the screen. A variation on this approach is to project a single beam on the screen and have a set of concentric circles replace the two straight lines. In the description of this approach the sample is always placed normal to the line of sight so as not to include lateral deviation in the measurements.

The accuracy of this approach can be estimated using the fact that the two reference lines are 1/2 inch apart and the line widths used in optical distortion evaluation are 1/16 inch wide at the grid board location. At a distance of 25 feet, a line width of 1/16 inch corresponds to an angular resolution of ± 0.37 minutes. Although not resolvable from a distance of 25 feet, the line image can be resolved to 1/16 inch; and this is a conservative estimate of the accuracy of this technique in measuring beam or image deviation.

A similar approach is described in ASTM-D-881-48,[24] where the deviation errors are determined using a telescope and target. In this technique a line of sight is established by focusing a telescope on a target. The telescope must have cross hairs and the target will consist of concentric circles, cross hairs, or

straight lines. When the windscreen to be tested is placed in the line of sight, the apparent position of the cross hairs on the target is shifted. From the magnitude of the shift and the distance between the target and the test windscreen, the deviation of the line of sight can be calculated. Again by requiring normal incidence of the windscreen to the line of sight, the measurement will not include lateral deviation effects. In this measurement the telescope provides 15X magnification so the resolution is 15 times better than the eye visual resolution, or 0.067 minutes. The variation in deviation is calculated in the above approaches over the windscreen evaluation area to permit evaluation of the total windscreen area.

These techniques are all adaptable to a direct binocular measurement by using a double aperture on the viewing or projecting optics. Binocular disparity for these double projections or viewing systems can be determined by comparing the superposition of the two projected or viewed targets instead of referencing to the true line of sight.

To permit evaluation of angular deviation while evaluating the windscreen installed at the design angle, the deviation introduced by the windscreen is measured using a collimated probe beam. This technique has been described in a recent McDonnell Douglas Corporation report[25]. A telescope is used to define the line of sight of a collimated beam, and the telescope image of the collimated beam can be used to separate the angular deviation from the lateral deviation. Since all parallel rays, regardless of lateral displacement within the aperture, will focus or image to the same location, only an angular deviation will cause the focus of the collimated beam to shift. The accuracy of this technique is less than one minute of arc because the angular size of the individual images is 10 minutes in the telescope, and the overlap of the two images can be readily determined to 1/10 their individual diameters.

This approach can also be accomplished using a collimated laser beam (one or two) and a position sensitive detector. Task[8] has described this approach for mapping the angular deviation over a windscreen. A movement jig held the windscreen at the installed angle and moved the windscreen in azimuth and elevation about the pilot's design eye position.

The accuracy of any of these techniques is limited only by the target or graticule used. These tests are repeatable, objective, and easy to perform. Most of the parameters of interest (angular deviation and binocular deviation) are measured directly, requiring nothing further than a calibration of the target. However, determining overall distortion requires that many data points be taken.

A less quantitative method was proposed by A. L. Wickeser, et al.[21] A uniform light field is established by approximating a point source of light. The transparency is then inserted. Any variation of deviation will cause light and dark patterns to appear on the projection screen. This is the result of some beams being deviated to an area where other beams are incident, thus increasing the intensity in these areas and decreasing the intensity in the area where an undeviated beam would have been incident.

2.4.2 Grid Board Photography

The most commonly used techniques for distortion testing involve photographing a grid board through the transparency being tested. These techniques include (1) taking a single exposure of the grid board and measuring the slope[9,14,19] or magnification variations[2,19] of any lines; (2) taking a double exposure, one without the transparency in and one with the transparency in, and looking for "splits" in the lines of the two exposures[26]; (3) taking a triple exposure through the transparency, translating the transparency vertically between exposures, and measuring the "growth" of the grid squares;[27,28] (4) taking a single exposure

through a two-hole mask (a modification of number 3);[27] (5) just visually inspecting a grid pattern as seen through the transparency being tested[19].

All of the photographic techniques have much in common, and the equipment required is basically the same. This equipment includes (1) a well-illuminated standard grid board (generally 1/16-inch lines with 1-inch spacings); (2) a mount for holding and positioning the windscreen transparency; (3) a camera with a 4 inch by 5 inch format (speed graphic or equivalent); and (4) generally some form of a drafting table to make measurements. This equipment is simple and inexpensive. Other equipment, such as digitizing equipment or a computer could, of course, be included in future work for the purpose of simplifying and expediting the data analysis, but the equipment required to actually perform the tests would remain about the same.

The parameters measured by these photographic techniques are also the same for the different approaches, with a possible limitation in the way the results are analyzed. These techniques do not directly measure absolute (total) or angular deviation; the lateral and angular deviation are coupled into one effect. It would be possible to determine the actual angular deviation to the undeviated beam by referencing the data found through the windscreen to the undeviated data and subtracting a calculated lateral displacement found by other means. This process would be laborious and unnecessary since the angular deviation can be measured directly by other techniques, that measure the change of anglular deviation. This is the major cause of any sudden changes in image figure, hence the distortion and lensing effect seen through the transparency. Since the grid board techniques are designed to test an entire area of the transparency at one time, these tests give an immediate indication of the overall distortion of the image caused by the transparency as it would be seen when in use. The direct analysis of the data received from the grid board photographing gives the point-by-point change in

deviation. The time involved and the accuracy of the quantitative results are different for the different techniques and will be discussed later. Further analysis and numerical comparison of the data can give a measure of binocular disparity. From this information, a measure of the anamorphic distortion, the amount of variation of lensing between a horizontal and vertical line of sight, can be derived.

The differences between these grid board photography techniques are the result of different analysis procedures. To obtain accurate, quantitative, objective, and repeatable results with any of these techniques requires a fairly laborious procedure by trained personnel.

2.4.2.1 Single Exposure Grid Board Photographs[2,9,14,19]

The procedure for the single exposure technique is to photograph the grid board through the transparency. This may be done at a number of locations (left eye position, right eye position, design eye position). Some tests also require that a reference photograph be taken without the transparency inserted. The slope of any grid lines or variations in magnification of the grid square is then measured, using a drafting table or plotting the coordinates of selected points and com-paring the measurements to the reference photograph. Grid slope techniques are used in the evaluation of the F-111.

From the ratio of grid magnification for the photo raphs taken with and without the transparency in place, the windscreen quality factor called lens factor can be determined. This quality factor is used for evaluation of F-111 windscreens, and the measurements are made at different areas over the windscreen.

A second quality factor used for the F-111 windscreen evaluation is called the displacement grade.[2,19] The displacement grade is given by measurement of the maximum displacement of the horizontal and vertical grid lines and is found by adding the maximum vertical displacement of any horizontal grid line (in

hundredths of an inch) to the maximum horizontal displacement of any vertical grid line, and by multiplying the sums by 1000. Again the measurements are made at different areas over the windscreen. These measurements are limited by the accuracy of the measuring instrument and the accuracy of the resulting statistical calculations. A trained individual could make these measurements fairly accurately. However, a trained and experienced person may also tend to make "rule of thumb" estimates to speed up this laborious task.

A point-by-point comparison of the test photographs to the reference photograph can also be performed. This data can then be analyzed into other measurements of interest.

The accuracy of the measurements can be estimated from consideration of the fact that the distortion is determined from photographs showing 14 to 16 grids to the inch and that a line position can be measured to an accuracy of 0.01 inch with the drafting equipment now used. Slope tolerances of the F-111 are 1/20, and slope tolerances of 1/10 to 1/20 are usual. These measurements are usually taken over distances greater than 2.5 inches, and if a deviation of 0.01 inch can be determined over 2.5 inches, the minimum measurable slope error is 1/250.

2.4.2.2 Double Exposure Grid Board Photographs [26]

The procedure for the double exposure techniques is to photograph the grid board without the windscreen in place, then to insert the windscreen and take a second exposure on the same photograph. Any distortion caused by the windscreen will cause "splits" between the grid lines photographed before inserting the transparency and the grid lines photographed through the transparency.

The simple approach to analyzing this data is to divide up the photograph into "field of view" areas and to count how many splits are seen in each area. The judgment of whether a line is "split" or not may vary from one inspector to another. This type

analysis requires some experience for the results to be repeatable. To do a more quantitative analysis, the actual split separation and length must be measured. After this laborious task, a determination of acceptable maximum values (arbitrary units) would be made. Since this process cannot be easily automated, it is limited to giving an overall picture[11] if it is to be analyzed easily.

2.4.2.3 Triple Exposure and Two-Hole Mask Technique[27,28]

The procedure for the triple exposure technique is to take three exposures on the same photograph, translating the windscreen vertically by a specified distance between exposures. A modification of this same technique is to take a single exposure through a mask with two holes displaced vertically. The variation of deviation and lensing is then obtained by measuring the change in the size of the grid squares. The theoretical objective of this method is to simulate dynamic flight conditions rather than to rely on a statistical comparison. Therefore, this method is aimed at measuring the rate of change in deviation. The test still basically measures the change in deviation, but it also references this change to a fixed dynamic change. This procedure gives an overall view of widespread distortion (lensing). Measuring localized distortion quantitatively becomes laborious, since it is basically a variation of the split line technique. The photographs may contain too much information to make an area-by-area analysis of the windscreen, and binocular deviation would be difficult to determine with this technique.

A summary evaluation of the optical distortion techniques is shown in Table 2.5, indicating the parameters tested and evaluated, whether the techniques involve evaluation of psychophysical effects, time required for data evaluation, the cost and complexity of instrumentation, the complexity of the technique, the repeatability or precision of the technique, the objectiveness or subjectiveness of the technique, and comments about the technique.

TABLE 2.5. REVIEW OF OPTICAL DISTORTION TESTING TECHNIQUES

Tests	a. Deviation (Coupled Lateral and Angular)	b. Angular Deviation	c. Rate of Change of Angular Deviation	d. Binocular Disparity	e. Overall Distortion
1. Project a straight line between 2 limiting straight lines.[22]	YES	Normal incidence required for windscreen illumination	Requires comparison of point to point measurements	Requires simultaneous projection of two lines	Must be extrapolated
2. View or project a graticle through a telescope with a reticle in it.[8,22]	•	•	•	Requires simultaneous projection of two graticles	Immediate and direct
3. As 1 and 2 but with a double viewing or projecting aperture.[22]	•	•	Immediate and direct but only for two points	Immediate	•
4. Transmit two collimated beams and evaluate at a common focus.[8]	NO	Direct	•	Immediate (angular deviation only)	•
5. Project a uniform amplitude diverging light beam and look for light and dark patterns.[22]	YES	NO (coupled with lateral deviation)	Immediate and direct	Not directly obtainable	Direct
GRID BOARDS					
6. Single exposure made of grid board. Evaluate line slope, lensing or displacement grade.[3,5,14,19]	NO	Must be extrapolated	Direct	Must be extrapolated	Immediate
7. Double exposure made of grid board. "line splits" measured or counted.[26]	•	•	•	•	•
8. Triple exposure made of grid board. Evaluate line slope and lensing differences.[27,28]	•	•	•	•	•
9. Single exposure made of grid board through a two hole mask. Evaluate line slope and lensing differences.[27]	•	•	•	•	•
10. Use trained inspectors to view grid board and compare to standard photo or windscreen.[19]	•	NO (coupled with lateral deviation)	•	YES	•

f. Anamorphic Distortion	Time to Analyze Results	Complexity and Cost of Equipment	Level of Experience to Perform Test and Analysis	Technique Accuracy	Comments
Must be extrapolated	Immediate for a and b, time consuming for others (4-6 hrs)	Simple and moderate cost-under $1 K	None for a and b, limited amount for others	$\pm$0.37 min of deviation for 1/16" line image	Limited for direct evaluation
Immediate and direct	"	Simple - telescope equip. and mounts $1 K-$2 K	"	15X telescope, so resolution is 0.067 min, accuracy < 1 min	Better accuracy than 1 and adaptable to evaluation of binocular disparity
-	Immediate for a, b, d, and f laborious and long for c,e (4-6 hrs)	"	None for a, b, d, and f, limited amount for c and e	$\pm$0.37 min or $\overline{0}$.067 min	Adaptation of 2 to a binocular disparity technique
Must be extrapolated	Immediate for b and d, laborious and long for c,e, and f (4-6 hrs)	moderate-laser required $2.5-$3 K	Limited amount for all task	< 1 min	Basic binocular disparity technique
NO	Immediate	Very simple under $500.	Limited to extensive depending upon information required	Qualitative test, limited by human judgment	Visual technique for evaluation of windscreen from variations in direction of transmission, subjective
YES	Laborious and Long with present evaluation techniques	Simple photo equipment and mounts $1.5K - $2 K	Moderate for photography and data evaluation	Slope error *1/250*, 0.01 inch accuracy in any line position	*Present data analysis* technique very laborious
"	Moderate	"	"	———	———
"	Laborious and Long	"	"	Slope error of 1/250, 0.1 with accuracy in any line position	Can be confusing to analyze
"	"	"	"	"	Can be confusing to analyze
"	Immediate	Simple under $700	Requires trained - experienced inspectors	Qualitative test, limited by human judgment	This is a realistic test to which all others must ultimately relate, but it is subjective. This is the only technique which directly evaluates psychological effects.

2.5 SUMMARY

This report summarizes a literature search done to identify techniques now used to assess aircraft windscreen optical quality.

The optical effects that were found to be evaluated in windscreen optical quality measurements included optical distortion, angular deviation, optical defects, optical transmission, haze, multiple imaging, binocular disparity, and birefringence-produced rainbowing. For each optical effect the techniques used for measurement were evaluated to determine their effectiveness and whether there was agreement on what techniques were best suited for evaluation of the different optical effects. Agreement was good on the best way to evaluate all the optical effects except optical distortion, birefringence-produced rainbowing and multiple imaging.

The task emphasized the study and evaluation of techniques for measurement of optical distortion.

SECTION 3

EXPERIMENTAL EVALUATION OF WINDSCREEN TESTING TECHNIQUES AND FOUR F-111 WINDSCREENS

A variety of windscreen testing techniques were evaluated using windscreens supplied by AMRL. These techniques are outlined in Section 2, with the exception of the binocular testing extensions addressed in detail in this phase of the program. Specific techniques investigated were the following:

1. Grid board photographic techniques, because of their w .e and general use.
2. Telescope and target measurement, because it is a simple and direct procedure.
3. Laser beam deviation measurement, because it allows more versatility than other techniques but is as simple in principle as the telescope testing techniques.
4. Some interferometry systems, because of the known high precision obtainable with interferometry.

3.1 GRID BOARD PHOTOGRAPHY

Acceptance testing of the Air Force's aircraft windscreens usually includes grid board testing, that is the visual observation and photographic recording of a grid board, through a windscreen. In evaluating this approach, both single and multiple exposure techniques were studied. The multiple exposure techniques permit the evaluation of binocular effects.

3.1.1 Single Exposure Techniques

The main emphasis in the evaluation of grid board photography has been the grid line slope measurements (single exposure photography) currently used in the evaluation of F-111

windscreens. The photographic procedure for this technique is very simple. A 4-by-5 camera is placed at the design eye position and a single exposure photograph taken of the grid board through the transparency, with the windscreen in the installed position.

To allow for comparisons reference points were established on the grid board which gave a standard x-y coordinant system on the grid board. This referenced grid board (no windscreen) is shown in Figure 3.1. To evaluate a larger area than the grid board covers (3 ft by 4 ft), the grid board was moved around and a series of photographs taken. This gave an effective grid board size of approximately 5 ft high by 7 ft wide. Two of these composite photographs are shown in Figure 3.2 and 3.3. The grid line slopes are then measured from 8 by 10 photographs which are enlarged to give 16 grid sqares per inch (of undistorted grid squares).

Even though "taking the picture" is not difficult, a number of other factors must be considered. In comparing a grid board photograph taken without the windscreen in place to one taken through the windscreen, it must be remembered that the insertion of the windscreen has increased the optical path length and required a refocusing of the camera. This means that the apparent grid board size has been changed (beyond lensing effects of the transparency). For most considerations this size change should be insignificant (about 1.5% decrease in size). A more significant concern is the control of the size of the enlargements (for comparison purposes). However, if only grid line slopes are to be measured this is not a great concern in that it will affect only the possible accuracy of the measurements. The camera and enlarger optics should not introduce any significant error and this can be verified by always including a reference grid board photograph of the undistorted grid board.

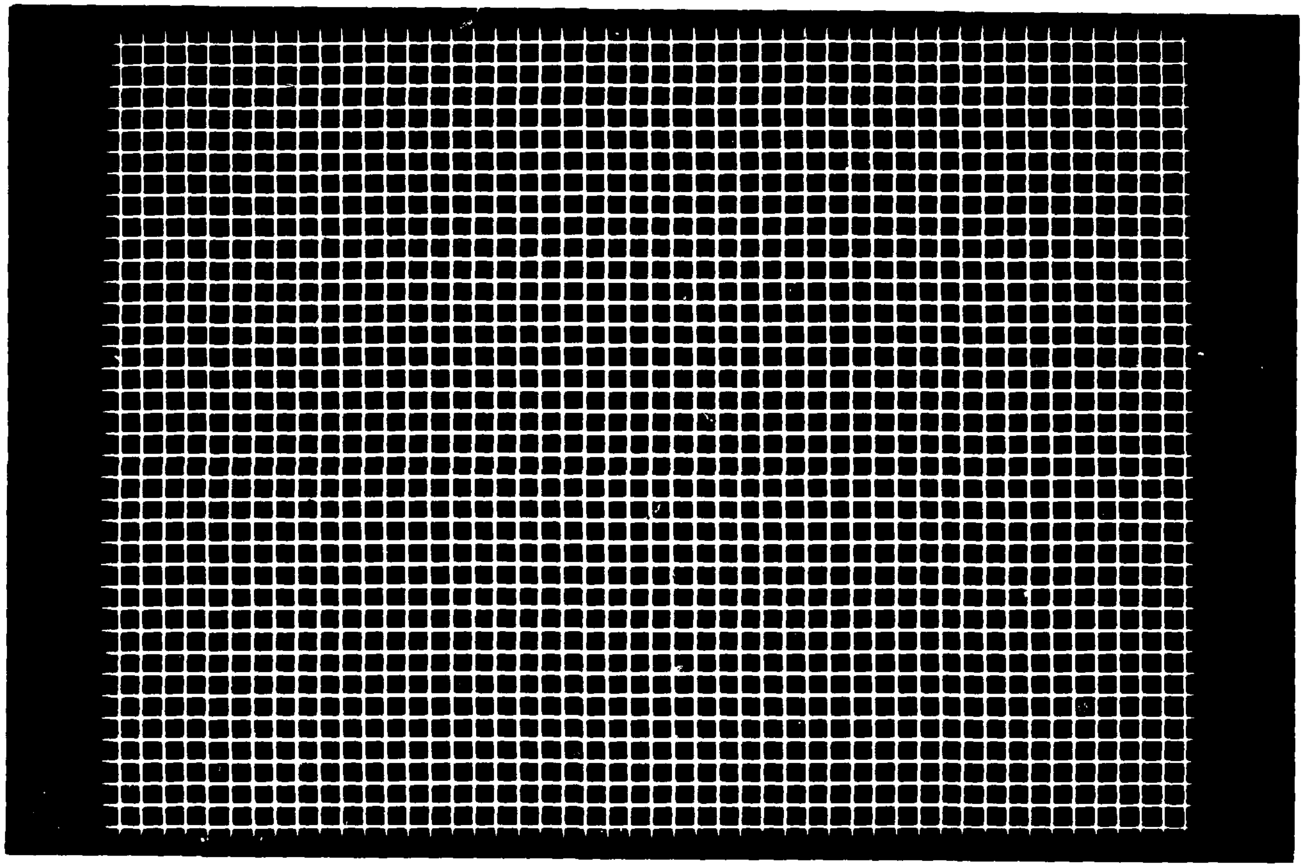


Figure 3.1. Reference Photograph of Grid Board Without Windscreen Inserted. The black out grid line intersections are used as a reference system for future reference. The center 4 point configuration points up (coordinates of center dot are (0,0)).

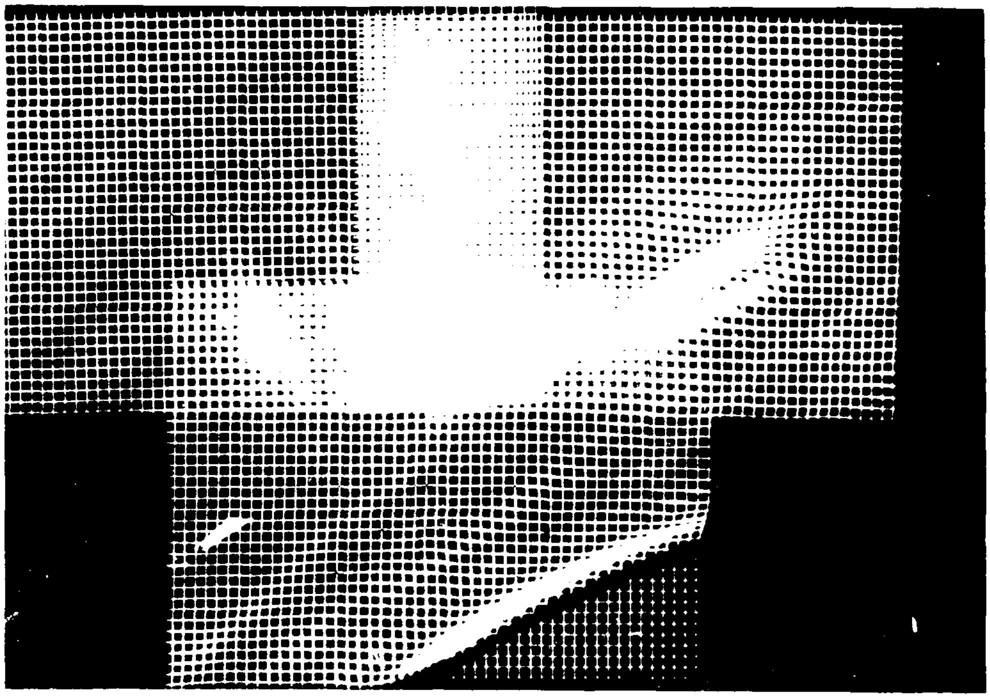


Figure 3.2. Composite Photograph of Three Different Positions of the Grid Board as Seen Through Windscreen STP-015-016.

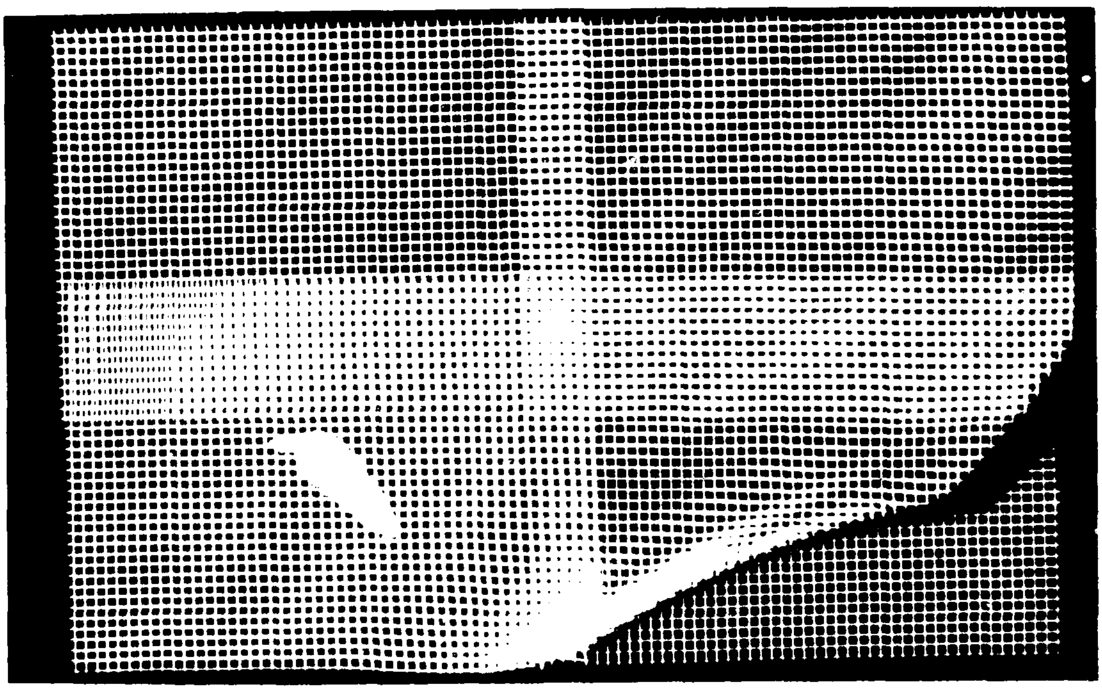


Figure 3.3. Composite Photograph of Four Different Positions of the Grid Board as Seen Through Windscreen E-015-153.

From the data taken the greatest source of error is in the actual measurement of grid line slopes. The line slopes being measured are not the slopes of straight lines but rather of curves, and the ability to measure any set of lines repeatedly is a matter of experience. This problem is compounded by the inherent error in the mechanical measuring instruments. This error could be reduced by electronic digitization and computer analysis of the curves directly.

An interesting effect seen in these photographs is the "highlighting" of distortion areas introduced by defocus (see Figures 3.2 and 3.3). By setting the camera to have a small depth of field, even slightly distorted areas "stand out" because they introduce a sudden, localized change of focus (as opposed to the gradual change from one edge of the grid board to the other). This indicates that these distortion areas exhibit a very definite lensing effect. The grid slope measurements are not made any easier by this defocus, but the areas of distortion can be seen more quickly.

3.1.2 Multiple Exposure Techniques: Their Use For Determination Of Binocular Disparity

As an extension of the direct single exposure method several multiple exposure techniques were tried. These techniques include taking one exposure without the windscreen inserted and one with it inserted; taking one exposure at the left eye position and one at the right eye position (a binocular disparity test); and taking three exposures with a vertical translation between each and checking for a change in grid square size. These techniques proved to be technically difficult for a number of reasons. First, 35 mm cameras (which the specifications generally called for) do not allow for accurate double exposures to be taken unless they are specially outfitted (with pin registration). Next re-aiming and focusing the camera, after it had been moved, was difficult, since not all points line up on the grid board for each exposure. However, as the eyes

look from one point to another they tend to "merge" the two images at that point and "average" the others. Even after a reason able realignment has been accomplished using a 4 x 5 camera, it is difficult to reload the film accurately to the same location. This problem of camera movement and film alignment is overcome by keeping the grid board and camera fixed and translating the windscreen, in a parallel fashion, from one eye position to the other.

A more satisfying method of obtaining multiple exposures is to overlay the negatives. All of the various exposures can be taken separately, then many different combinations of multiple exposures can be examined by overlaying the negatives and printing the multiple exposures as one photograph. When overlaying the negatives the problem of alignment can be more easily dealt with in real time, without the need for many photographs which must be developed first to see if they are accep table. An interesting effect observed was the moire patterns, which followed the deviations (making the deviations stand out), occurring when a negative was overlayed on a positive at a slight rotational angle. These patterns may be worth further evaluations.

Binocular disparity measurements were made using both the above approaches. Two single exposure photographs were taken, one at each eye position, and one double exposure photograph was taken from one exposure at each eye position. These exposures were taken in such sequence to allow exposures at each eye position to be the same. The double exposure photograph shows a vertical translation which increased to the upper left of the photograph with some non-linear horizontal translation apparent in the central area as shown in Figure 3.4. Figure 3.5 shows the results of the superposition of two single exposure photographs. Because it was not possible to accurately superimpose the two single negatives, the results of Figures 3.4 and 3.5 are not the same. To accurately superimpose two negatives would require one or

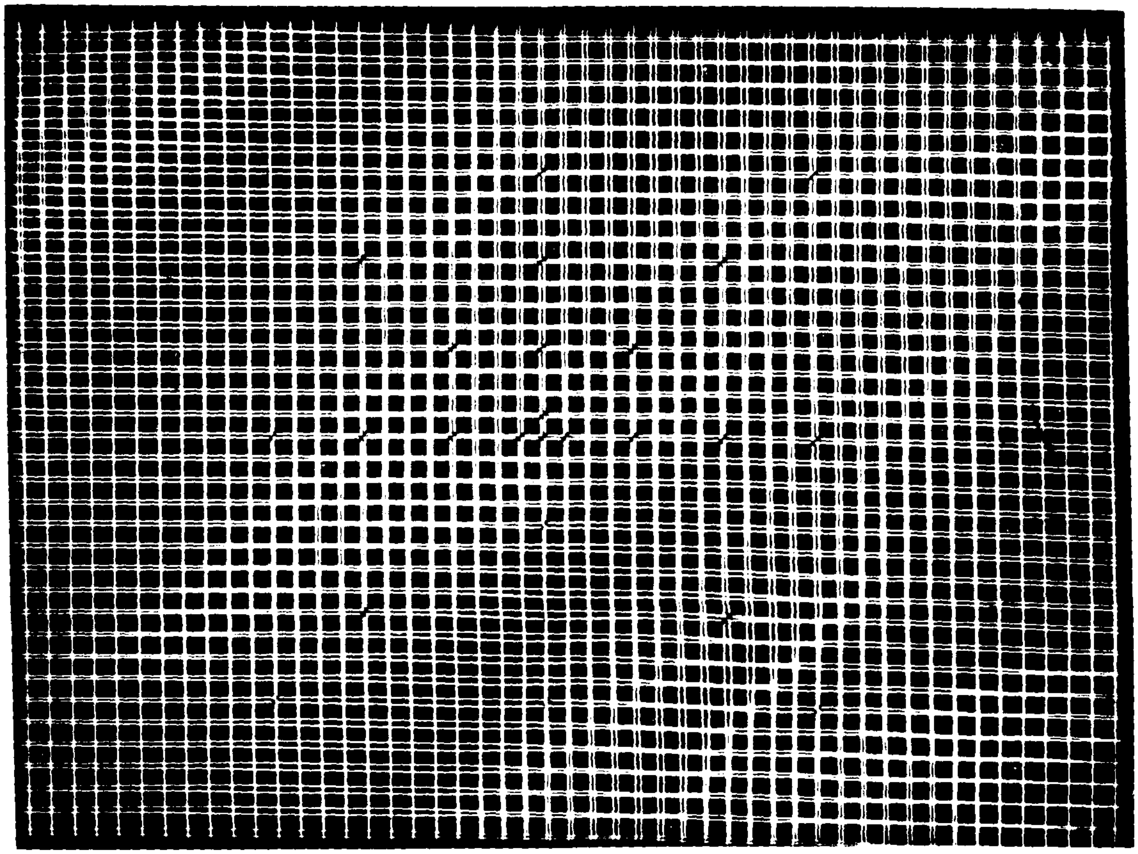


Figure 3.4. Double Exposure of Grid Board from Left and Right Eye Positions for Windscreen E-015-153.

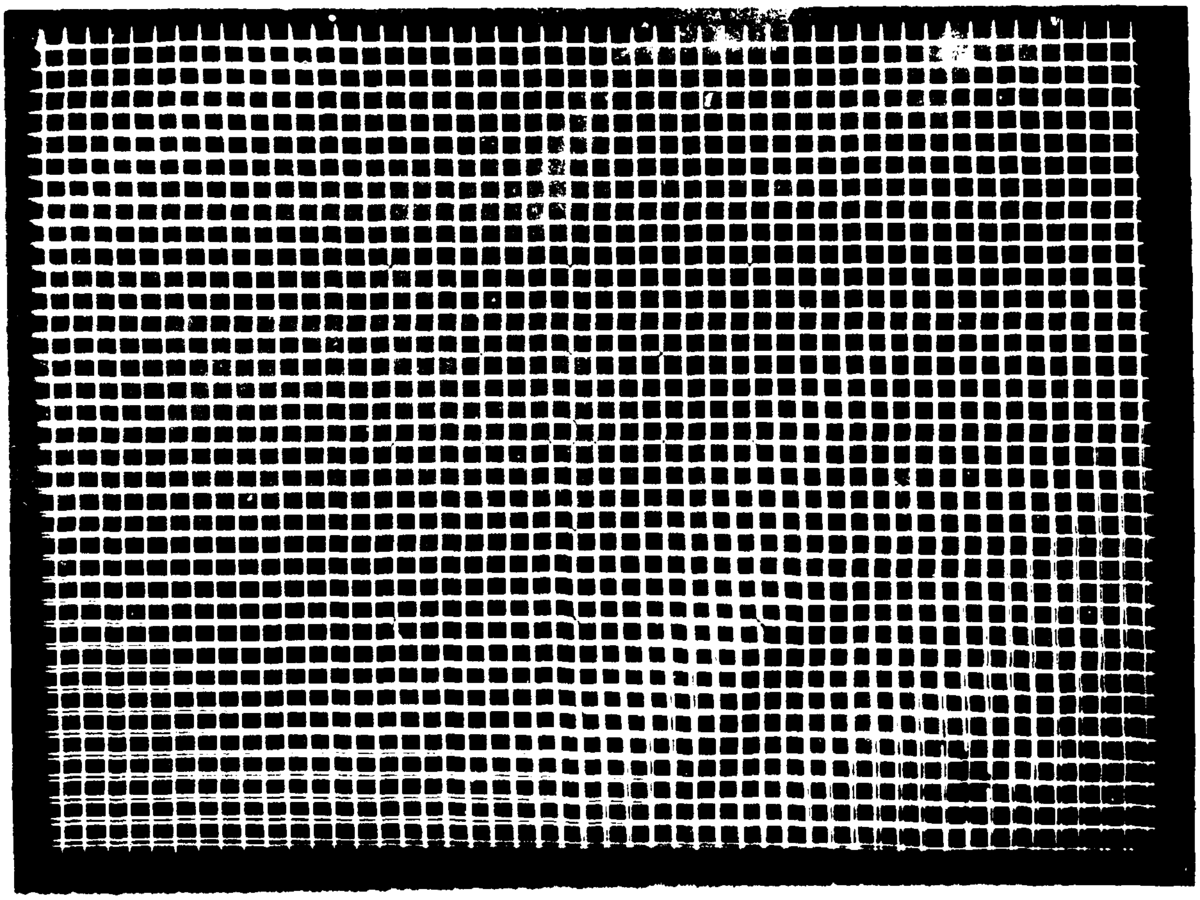


Figure 2.5 Overlay of Sample Specimen Photographs Taken at Left and Right Eye [illegible] Specimen [illegible]-153.

two well defined reference points that do not move between exposures and are not seen through the windscreen. This could be done if such an approach is used for windscreen testing.

3.2 POINT-BY-POINT MEASUREMENTS

In this approach the windscreen evaluation is obtained by many separate measurements of the windscreen errors over the area of interest. Techniques developed have been based upon mapping the deviation of a collimated beam or some image.

3.2.1 Measurements Made with a Telescope and Target

To compare the grid board photography to a different technique and measurement unit, the total deviation was measured at selected points on the grid board as seen through the windscreen. This was done by aiming an alignment telescope, 7x-power with a 1 inch aperture, at a selected reference target, at a given point on the grid board (no windscreen inserted), then inserting the windscreen and noting the deviation. This setup is shown in Figure 3.6. Because the grid board is a diffuse, non-collimated light source, and the imaging system is working with finite conjugates, both the effects of angular deviation and lateral displacement are observed. This system then gives a measure of total deviation at that point.

A telescope system of this type gives a constant and reliable degree of accuracy, limited only by the target accuracy (this telescope has a usable resolution of less than 10 seconds of arc). Problems were encountered in realizing this accuracy in areas of the windscreen where there is considerable blurring and double imaging. In the case of double imaging there is an ambiguity as to which image to measure. The general blurring is the result of anamorphic lensing, which prevents focusing of the telescope on more than one "small" area at one time, thus making the measurements difficult if not impossible.

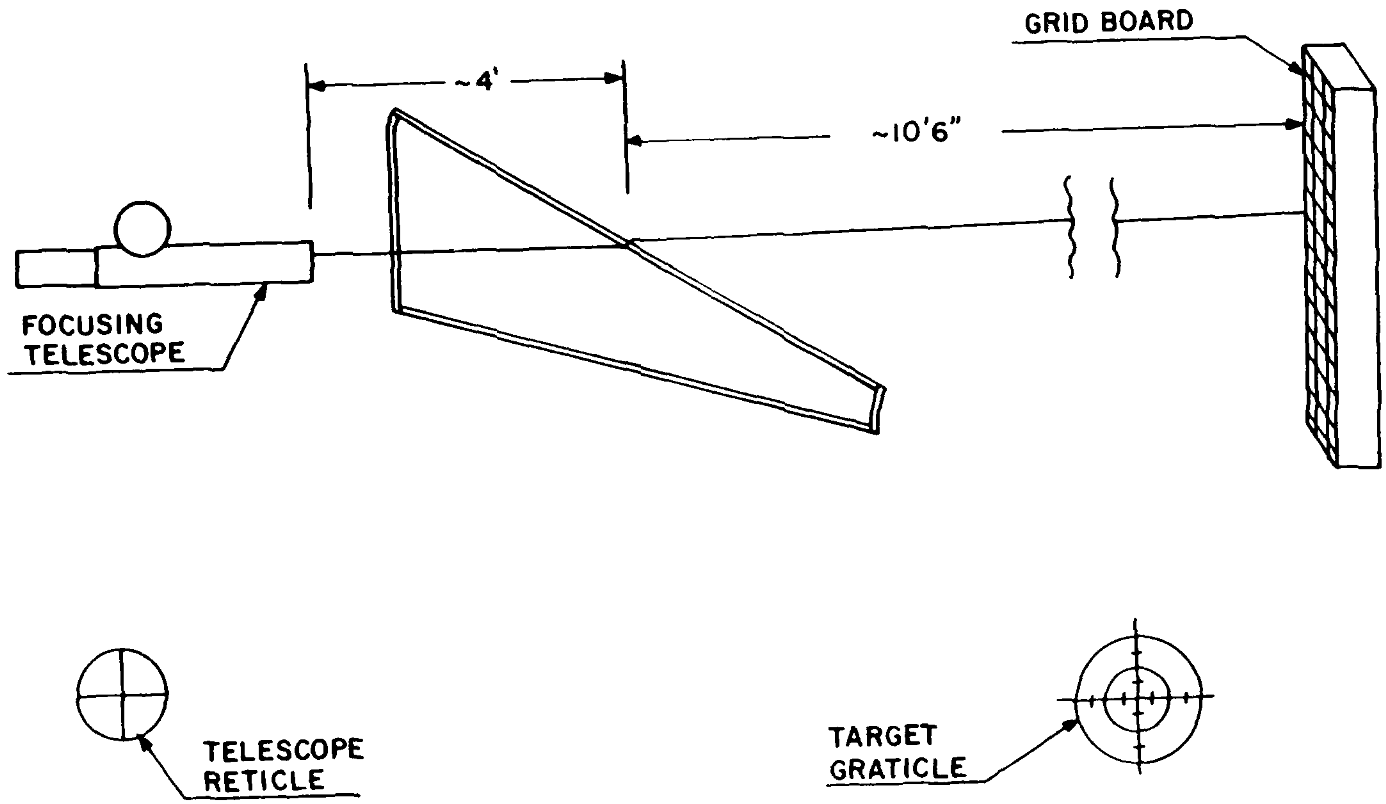


Figure 3.6. Telescope Measurements.

3.2.2 Laser Beam Deviation Measurements

These point-by-point measurements were performed using a laser beam. The procedure was the same as with the telescope (see Figure 3.7). The total deviation measurements obtained using the laser beam agreed with those obtained using the telescope system. These laser beam measurements were easier to interpret than were the telescope measurements. The "double images" could more easily be separated. Any drastic blurring tended to give a larger, warped spot, but it was still readable (with less accuracy). The laser beam scatter also showed if there was excessive scatter in a particular location.

To separate the angular deviation and lateral displacement, a lens was inserted and focused on the grid board. A lens will focus all parallel rays within its aperture (laterally displaced) to the same point. Therefore the position of this focus spot will only be sensitive to angular deviations. This was done in addition to just noting the change in spot position without the lens in place. For these measurements to be relevant to the measurement of windscreen optical distortion errors an accuracy of $\pm$ 1 minute of arc is required.

In the measurements that were made two systems were used. At first a lens with a 30 inch focal length was used and the limit of visual sensitivity was $\pm$ 7 minutes of arc. The sensitivity was decreased to $\pm$ 1.2 minutes of arc when a 90 inch focal length lens was used. A higher accuracy could also be obtained by using a position-sensitive detector to determine the beam deviation. Using a motorized mount to scan the windscreen, the detector could be used to drive a chart recorder, thereby giving an angular deviation map of the windscreen. If a detector array was used, the size and shape of the spot could also be analyzed (though this would probably require some software assistance).

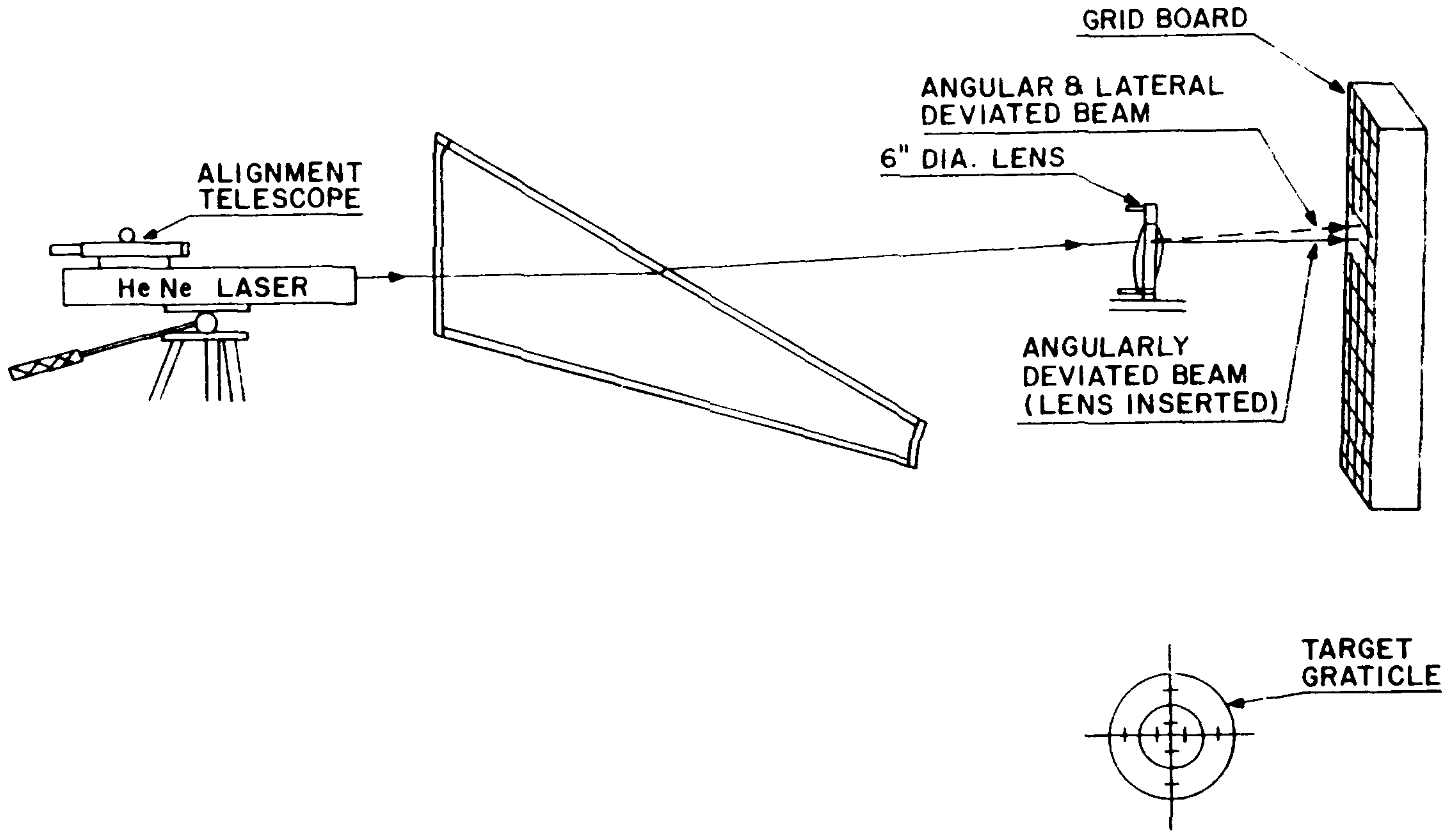


Figure 3.7. Laser Beam Deviation Measurements.

3.3 COMPARISON OF GRID BOARD SLOPE AND POINT-BY-POINT MEASUREMENTS

In the use of a slope technique for evaluation of a windscreen instead of point to point measurements the results will not describe the amount of constant displacement or deviation which may exist due to the windscreen geometry. Also, there is less accuracy obtainable from the grid slope method than from the point-by-point method. The first problem is due to the ambiguity of where to measure the slope, as mentioned previously. There is also a direct problem of measurement of the photographic data. If we take the limit of accuracy of the point by point system to be the accuracy to which the target can be measured ($\leq\pm$ 1/16 inch for the 90 inch focal length lens) this gives accuracy of close to $\pm$1 minute of arc. To realize this same accuracy on a photograph printed to 16 grid squares per inch, measurement must be made to less than .004 inch. This accuracy would be very difficult to obtain.

3.3.1 Difficulty and Time for Each Technique

The grid board photography techniques are simple to perform in the laboratory, and provide the overall distorting information in one hard copy for the record. The effort involved in the grid board photography occurs when the measurements are made. The desired accuracy and repeatability are not easy to obtain. On the other hand point-by point techniques are very laboratory intensive, which can be hard on the person taking the data (an effect which may itself introduce some errors). As mentioned before, this effort would be greatly lessened with a movable mount, automated mapping technique. There are still some out of the laboratory computations required to get the grid board information (which are not direct) since the pictures must be evaluated to get the desired data.

3.3.2 Error In Taking Grid Board Photographs

The procedure for taking the grid board photographs is straightforward. However, because many of the photographs must

be compared to each other or to a standard photograph, there are strict requirements on stability of the camera and repeatability of the position of the camera because any vibration will produce fuzzy pictures. A little vibration from the camera shutter is usually of little concern; however, in attempting to read these grid board photographs to less than 0.01 inch a shaky tripod will allow this much movement to occur. Another stability problem was encountered in taking binocular photographs where the camera must be translated between the two photographs without changing its longitudinal position (and hence the focus). Most camera tripods will "tilt" from side to side if the weight of the load is not evenly centered on the tripod. A heavy duty tripod was required to take correctly registered binocular photographs (translating the windscreen laterally). These photographs indicate that the windscreen does in fact introduce a "tilting" of the grid board image, which can not be accurately measured if the tripod itself may also be tilting.

These problems with camera stability also introduced a repeatability error. If the photographs of the grid board are to be compared, a stable and repeatable *reference point* with respect to the grid board must be maintained.

Another major source of error in taking the photographs is caused by focus errors. Any set of exposures which are to be compared later by overlaying the negatives must all be taken with the same focus setting on the camera. This is because any focus error (due to focus setting changes or tilts and translations of the camera relative to the grid board) will cause a change in magnification of the grid board. Any changes in the size, shape, or character of the grid board should be due to the windscreen under test. The windscreen should be the only optical variable.

3.3.2.1 Errors In Film Processing

The next process to consider for sources of errors is the actual processing and printing of the photographs. In developing

the film, there may be some shrinkage of the emulsion. Only non-linearities of this shrinkage are of concern in this system, and the non-linearities appear to be negligible. To insure uniformity in any such metamorphosis of the film, all photographs should be processed the same, preferably at the same time using the same chemicals and conditions of processing.

There is a greater possibility for error in making the enlargements than in developing the film. The same restrictions apply to the enlarger setup as to taking the pictures. The size and focusing should be set (as in taking the photo) by means of a reference photograph taken of the undistorted grid board without the windscreen in place. This setting needs to be accurate and to be maintained for the printing of the photographs to be compared. As before, the developing and processing should also be the same for all photographs to be compared. It should also be noted that, as with the camera, no corrections in terms of tilting of the film plane should be attempted. The only optical variable should be the windscreen. As with the emulsion of the negative, there is the possibility of paper shrinkage of the print. This should be monitored and minimized by use of a low shrinkage paper (such as type RC).

Neither the optics of the camera nor those of the enlarger should cause any significant distortion. Most photographic optics are of sufficient quality as to not introduce any such error. This can be checked from measurements of the reference photograph of the undistorted grid board.

3.3.3 Accuracy in Grid Board Slope Measurements Using Manual Reduction Techniques

A study was conducted to determine the accuracy of obtaining grid slope measurements from photographs of grid board distortion. The experiment was conducted with six unskilled subjects. Four photographs were mounted on a paper with a reference photograph, and two copies were given to each individual. Sixteen points were selected for evaluation.

Three points had the same slope value, and the other thirteen points were selected with varying degrees of slope.

The subjects were then given a ruler and told to measure the slope about the designated points in terms of the number of vertical grid lines traversed in the horizontal direction on the adjacent reference grid board photograph while traversing one grid square in the vertical direction on the adjacent reference grid board photographs. The straight edge was aligned tangent to the test grid board horizontal line at the point under evaluation. The results are shown in Table 3.1. The average error from the mean was found to be about twenty percent. Only fifty percent of the people in the sample obtained the same slope value for the duplicate points. Generally, the people who obtained the same value for the duplicate points did so within ten percent.

There are a number of possible errors in this study. In the case of duplicate points, the duplicate photographs may not have been mounted next to the reference grid photographs exactly the same. In this case a constant offset should be found, but was not. Also, some of the points may have been particularly difficult, but in actual testing these points could not be ignored. The largest factor is probably the experience of the people. Many subjects did not appear to have a clear understanding of what they were supposed to actually measure (or by what procedure). This problem could also exist in the windscreen manufacturing industry. By eliminating the people in the sample who expressed confusion, the average error dropped below fifteen percent. Experienced people with good equipment could probably reduce this error to less than ten percent. There would still be the problem of "fuzzy" points which could again give high discrepancies.

TABLE 5.1 REPEATABILITY OF GRID LINE SLOPE MEA[illegible]

Point	Average	Average error	[illegible] Average [illegible]*
1	26	4.5	[illegible]*
2	15	[illegible]	[illegible]4
3	26	5.5	[illegible]
4	36	9.5	[illegible]*
5	30	7	[illegible]4
6	45	5.5	[illegible]
7	37	8.3	[illegible]
8	37	6.5	1[illegible]*
9	39	11	[illegible]
10	36	[illegible]	[illegible]
11	24	10	[illegible]
12	21	5	[illegible]4*
13	42.5	[illegible].5	[illegible]
14	31.5	[illegible]	[illegible]
[illegible]	36.5	[illegible]	[illegible]
16	42	7	[illegible]

*The average of the average error (excludin[illegible]) was [illegible] percent. (76 data points)

3.3.4 Errors In Laser Beam Deviation Measurements

The different sources of error in mapping the windscreen errors using this technique are all instrumental. One source of error is the requirement for stable positioning of the laser. A single reference point should be maintained for any set of data (to within available settings), for all angles. For angular deviation measurements made using a lens to focus the beam (to eliminate lateral displacements), a stable, versatile mount is also required.

The positioning of the lens is also a possible source of error to consider. If angular deviation measurements are to be compared to total displacement measurements, the lens must initially be inserted so as not to deviate the undisturbed laser beam. In doing this, as in making the actual measurements, there is some uncertainty due to the finite size of the laser spot on the target. This error can be minimized in the alignment of the lens by retro-reflecting the beam from both the front and back surface of the lens back to the laser. Another error due to lens position is the focus error due to incorrect longitudinal positioning of the lens (not having the lens exactly one focal length away from the target). Such a longitudinal error of $\pm$ 4 inches in the positioning of a lens with a 90 inch focal length and a spot position measurement accuracy of 1/16 inch ($\pm$ 1/32 inch) would cause an error of only three seconds per minute of arc of deviation. Since the 90 inch focal length lens only gave an accuracy of about $\pm$ 1.2 minute of arc this error is not significant. In doing the actual comparison of angular deviation to total displacement, there is also an error caused by the uncertainty in the path length between the windscreen and a point on the grid board. The change in path length from the center of the grid board to the laser, to the edge of the grid board to the laser is approximately two inches. In calculating the effect of angular deviation on the beam from the windscreen to the grid board (so that the lateral displacement can be calculated) this

path length error introduced an error of one second per minute of arc deviation. This error is therefore insignificant. The limiting factor is then the accuracy limitation imposed by the focal length of the lens. This error of $\pm$ 1.2 minutes of arc will introduce an error of $\pm$ 0.1 inches in the calculations of the lateral displacements.

Most of the possible errors due to equipment positioning could be eliminated by using an accurately movable windscreen mount, thereby leaving the other optics stationary. This system could be easily automated using a computer controlled windscreen mount (or other means of position calibration) and position sensitive detector arrays (see Figure 3.8).

3.4 RESULTS OF WINDSCREEN MEASUREMENTS

During the experimental evaluation of technique used for measuring windscreen optical distortion, four different windscreens were used. Table 3.2 shows the serial number, Aero Medical Research Laboratory number, type, and optical quality of the four windscreens. From the measurements made it is possible to make the following useful observations about the distortions caused by windscreens:

(1) The lateral displacements varied only moderately over any one windscreen.

(2) The lateral displacements measured were attributable to the windscreen geometry and thickness (25 mm).

(3) The angular deviations were produced by both windscreen geometry and windscreen errors.

(4) The main contributing factor to windscreen distortions were the angular deviations.

3.4.1 <u>Windscreen Displacement Considerations</u>

The lateral displacement effects are observed for nonnormal incidence of light from the grid board or laser beam used for point-to-point measurements. For a windscreen of thickness t,

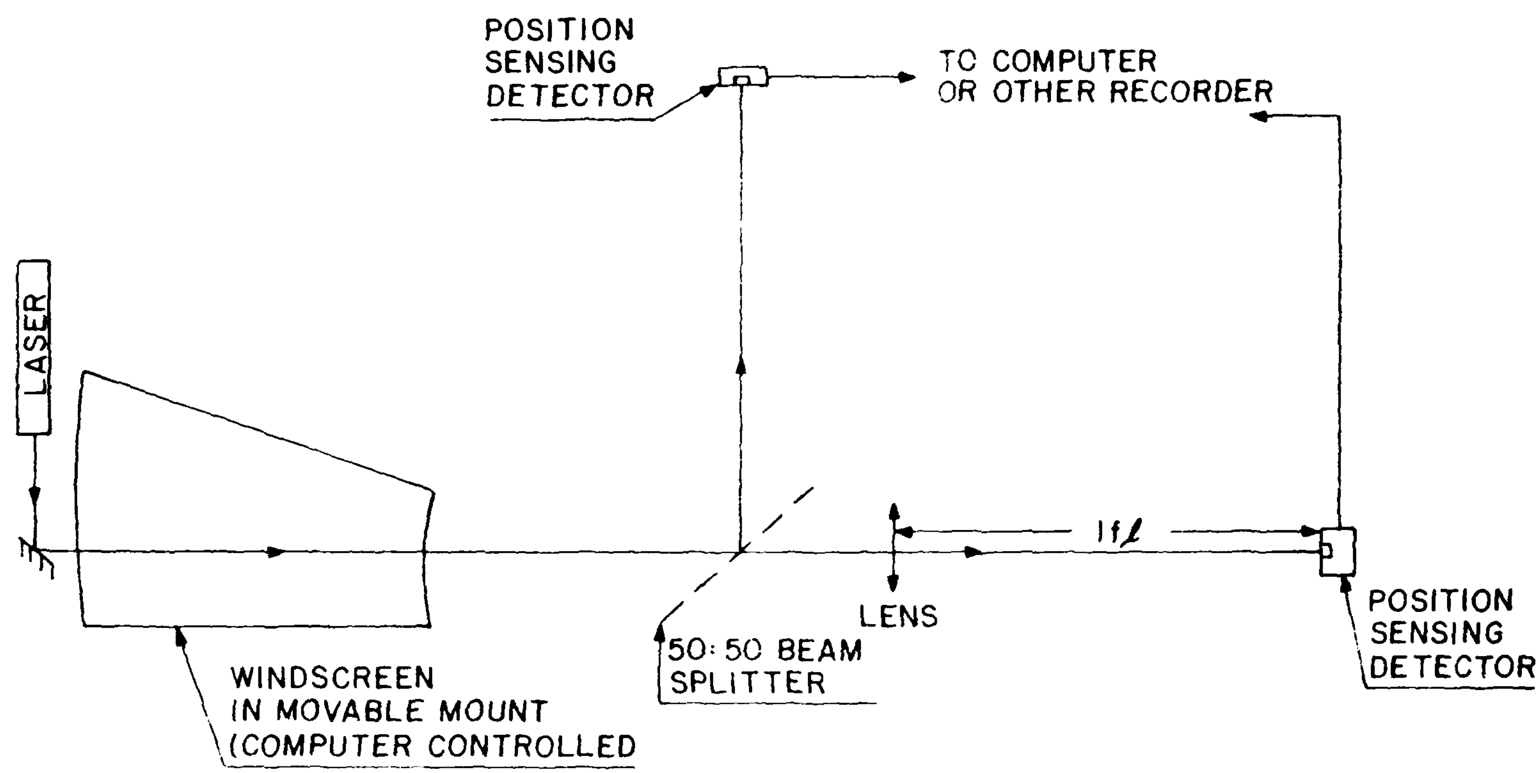


Figure 3.8. System for Measuring Angular Deviation and Lateral Displacement Caused by an Aircraft Transparency Using Movable Windscreen Mount.

TABLE 3.2 SAMPLE WINDSCREENS

Type	Serial Number	AMRL Number	Optical Quality Comments
Standard Laminated	STP-015-016	None	Large Localized Errors
Standard Laminated	E-015-153	17	Bad Multiple Imaging
Lightweight Laminated	157 300-51A S/N017	13	Good Optical Quality
Standard Laminated	E-016-142	20	Bad Binocular Disparity

angle of incidence on the windscreen θ, and angle of refraction at the windscreen θ' the lateral displacement Δy is given by

$$\Delta y = t\ [\tan\theta - \tan\theta'] \tag{6}$$

Table 3.3 shows how the lateral displacement will vary with the angle of incidence for a laminated windscreen of 25 mm thickness (n 1.5).

TABLE 3.3 LATERAL DISPLACEMENT VARIATION WITH ANGLE OF INCIDENCE ($t = 25$ mm, $n = 1.5$).

θ (Angle of Incidence)	Δy
0°	0
10°	1.52 mm
20°	3.24 mm
30°	5.59 mm
40°	9.12 mm
45°	11.63 mm
50°	14.94 mm
60°	25.62 mm
70°	48.59 mm
80°	120 mm

A variation in lateral displacement with variation in windscreen thickness will also be observed. Typical variations in thickness for the F-111 windscreen are less than 0.05 inches. The F-16 has much larger variations in windscreen thickness because of the extreme changes in curvature. However, in critical area viewing a variation of 0.05 inch or less should be possible. The variation in lateral displacement with windscreen thickness errors can be obtained from the derivative of equation 6. For windscreen thickness errors of t the variation in lateral displacement $\delta(\Delta y)$ will be

$$\delta(\Delta y) = y\ \frac{\delta t}{t} = t\ [\tan\theta - \tan\theta'] \tag{7}$$

Table 3.4 shows how the variations in lateral displacement will change with the angle of incidence for errors in windscreen thickness of 0.05 in.

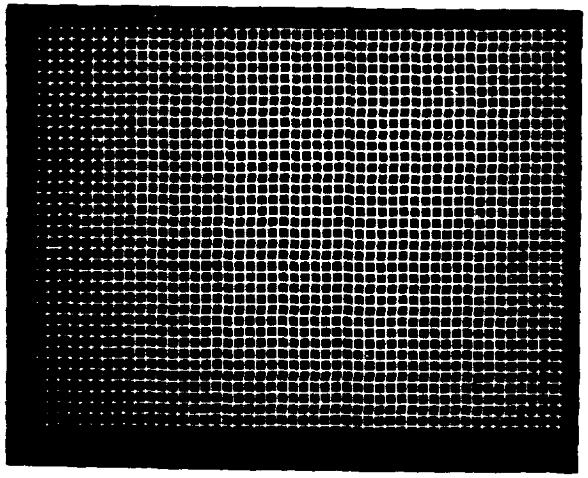
TABLE 3.4 LATERAL DISPLACEMENT CHANGE AS A FUNCTION OF THE ANGLE OF INCIDENCE (δt = 0.05 in, n = 1.5)

θ(Angle of Incidence)	$\delta(\Delta y)$
0°	0
10°	.075 mm
20°	.16 mm
30°	.28 mm
40°	.46 mm
45°	.58 mm
50°	.75 mm
60°	1.28 mm
70°	2.42 mm
80°	6 mm

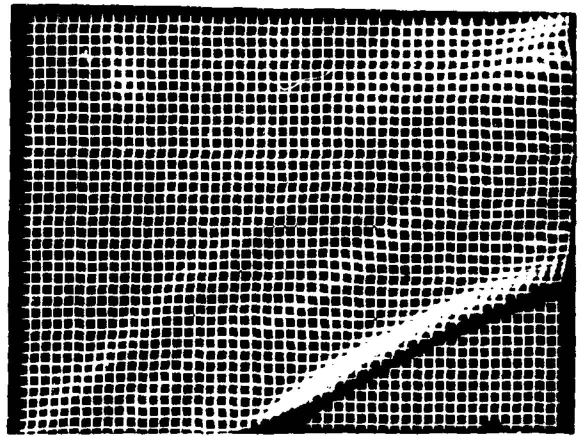
In addition to these lateral displacements any measuring system that can not discriminate between lateral displacement and angular deviation effects will see displacement effects produced by the angular deviation. At the design eye position the distance from the windscreen can be 1 m or more. For a 10 minute deviation error the displacement at 1 m is 1.94 mm.

3.4.2 Grid Board Photography and Point-By-Point Measurements of Laminated Windscreen STP-015-016(F-111)

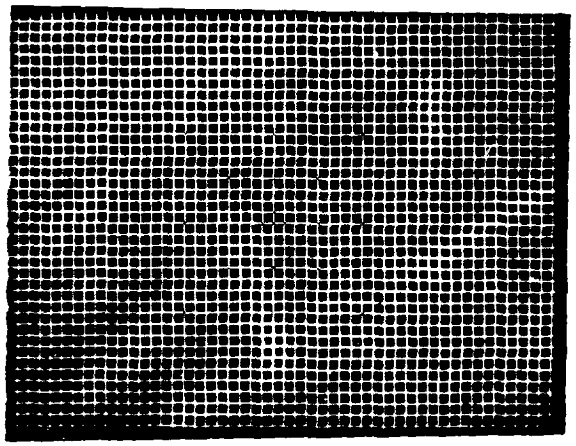
The windscreen had been rejected for use by the Air Force because of its large localized optical distortion. Figure 3.9 shows grid board photographs without the windscreen in place, the lower central area of the windscreen, upper left area of the windscreen, and the upper right area of the windscreen. In the lower central area and upper right area of the windscreen the large localized distortions of the grid board pattern are very



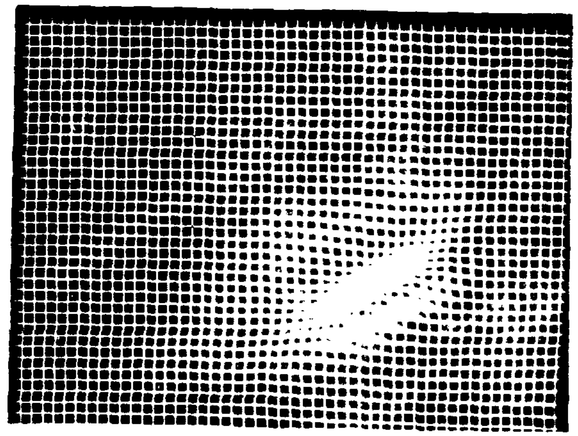
(a) Reference Grid Board



(b) Lower Central Area of Windscreen



(c) Upper Left Area of Windscreen



(d) Upper Right Area of Windscreen

Figure 3.9. Grid Board Photographs of Windscreen STP-015-016 LF-1111

apparent. Measurements of the grid board slopes (number of vertical grid lines traversed in the horizontal direction on the adjacent reference grid board photograph, while one grid square is traversed in the vertical direction on the adjacent reference grid board photograph; the straight edge is aligned tangent to the test grid board horizontal line at the point under evaluation) found the slope errors the worst in the lower central area ([illegible]) and the upper right area ([illegible]). The slope errors were not as bad in the upper left of the windscreen, and the worst distortion found was [illegible].

This was the first windscreen evaluated using laser beam deviation mappings. The lateral displacements varied only moderately and the variations seen were attributable to the geometry and the varied thickness of the windscreen. The measured angular deviations were influenced by both the windscreen geometry and distortions. The magnitude of the angular deviations varied between [illegible] and [illegible] minutes of arc. The angular deviation errors were [illegible] contributing factor to windscreen distortion [illegible].

3.4.[illegible].1 Localized Anomalies

The localized anomalies such as the large "bulls eye" effects seen are characterized by a fast rate of change of deviation (about [illegible] to 5 minutes of arc per grid board square). These angular deviations were primarily in the horizontal direction following the design of the windscreen. Large distortion areas [illegible] in the type of asymmetric, distorted lens that they look like. There were large angular deviations (up to 40 minutes of arc) measured across these anomalies. A mapping of the [illegible] deviations seen in the [illegible] anomaly is shown in Figure [illegible]. This mapping has the same form as a mapping of purely angular deviations shown in Figure 3.11. These anomalies seem to be greater than the angular deviation specifications of most current tests. This introduces power into these areas of the windscreen. However, these "lenses" do not necessarily have the same power in any two directions.

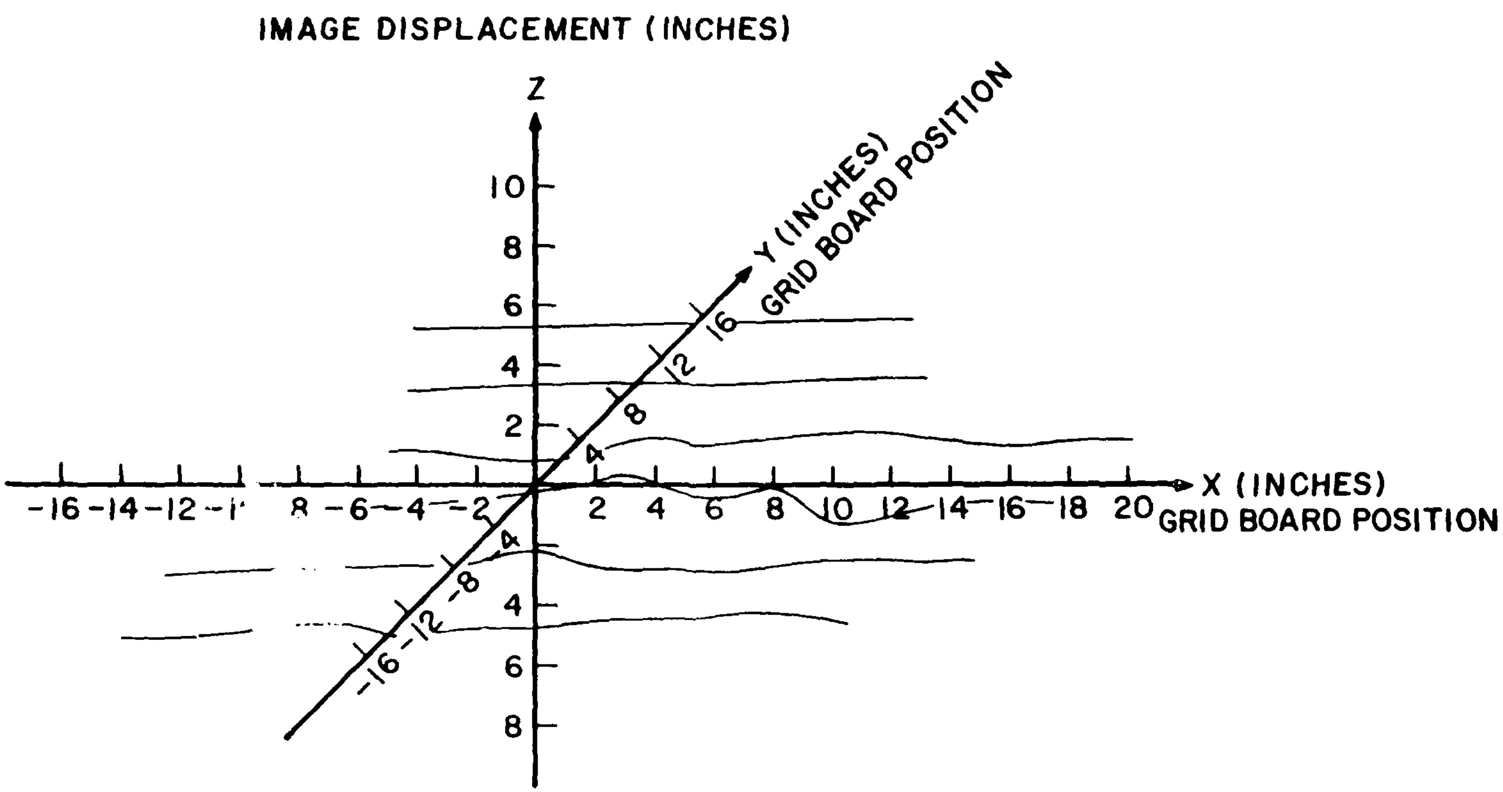
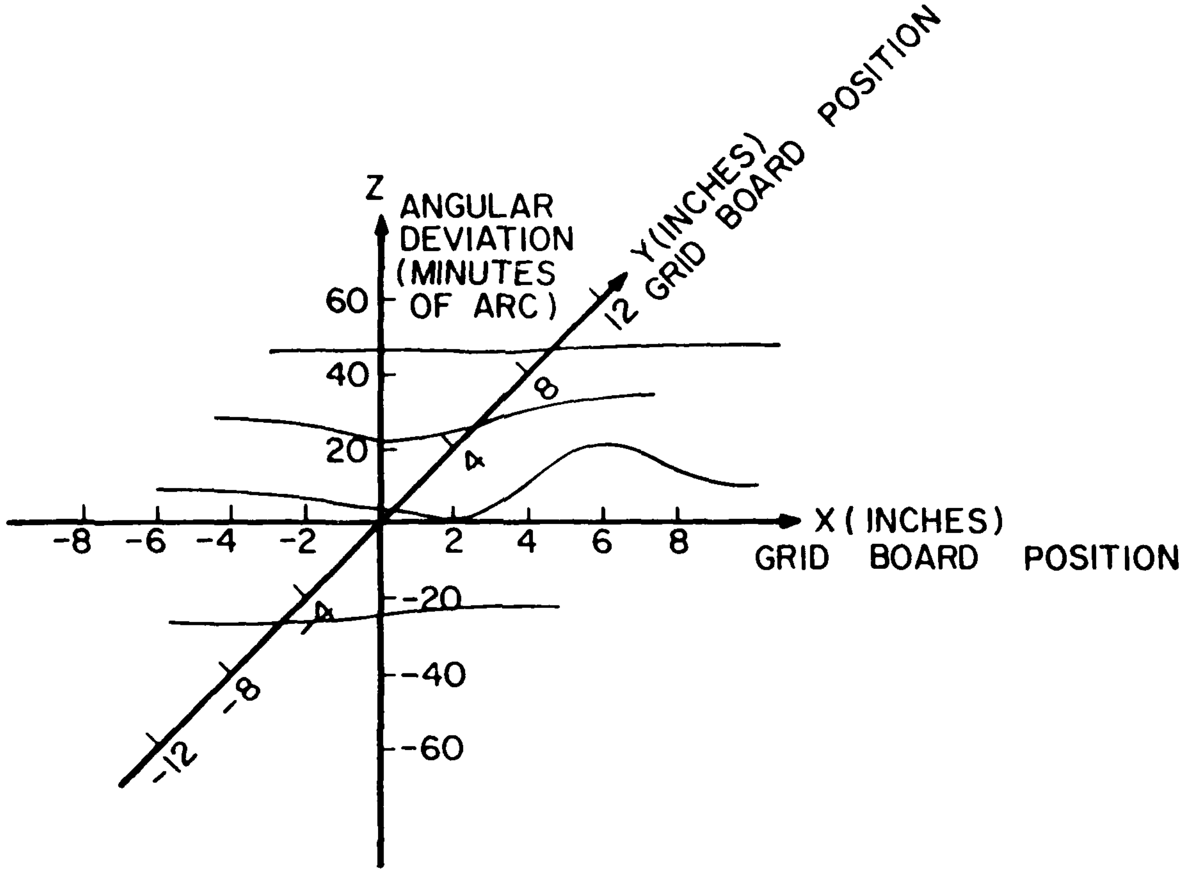


Figure 3.10. Total Deviation Contour of Local "Bulls Eye" Distortion for Windscreen STP-015-016.



igure 3.11. Angular Deviation Through the "Bulls Eye" Region of The Windscreen STP-015-016.

3.4.[illegible]

[illegible] windscreen [illegible]

in terms of [illegible] and repeatability, [illegible] the work easier. The lens used to make the [illegible] deviation measurements was changed [illegible] length to increase the measurement [illegible] windscreen angular deviations. [illegible] measurements to calculate the lat[illegible] windscreen (by subtracting angular [illegible] deviation) gave an accuracy in the [illegible] ment of ± 0.1 inch.

3.4.[illegible]

Figures 3.12 and 3.13 show photographs of the [illegible] grid board as a reference photograph and of the grid board as seen through the windscreen. The photographs were taken without changing camera focus or position. The windscreen mount was improved so that the windscreen can pivot around the [illegible] eye position. The mount design also permitted the removal and accurate repositioning of the windscreen.

Figures 3.4 and 3.5 show two binocular photographs taken with this windscreen. The two techniques used to obtain the binocular photographs were a double exposure with the [illegible] at each eye position and a superposition of two separate photographs from each eye position. As described in section 3.[illegible] the results of trying to photograph the two separate exposures were not satisfatory because of the lack of fixed reference points that are present in both exposures and are not viewed through the windscreen. The grid board distortion for this windscreen is

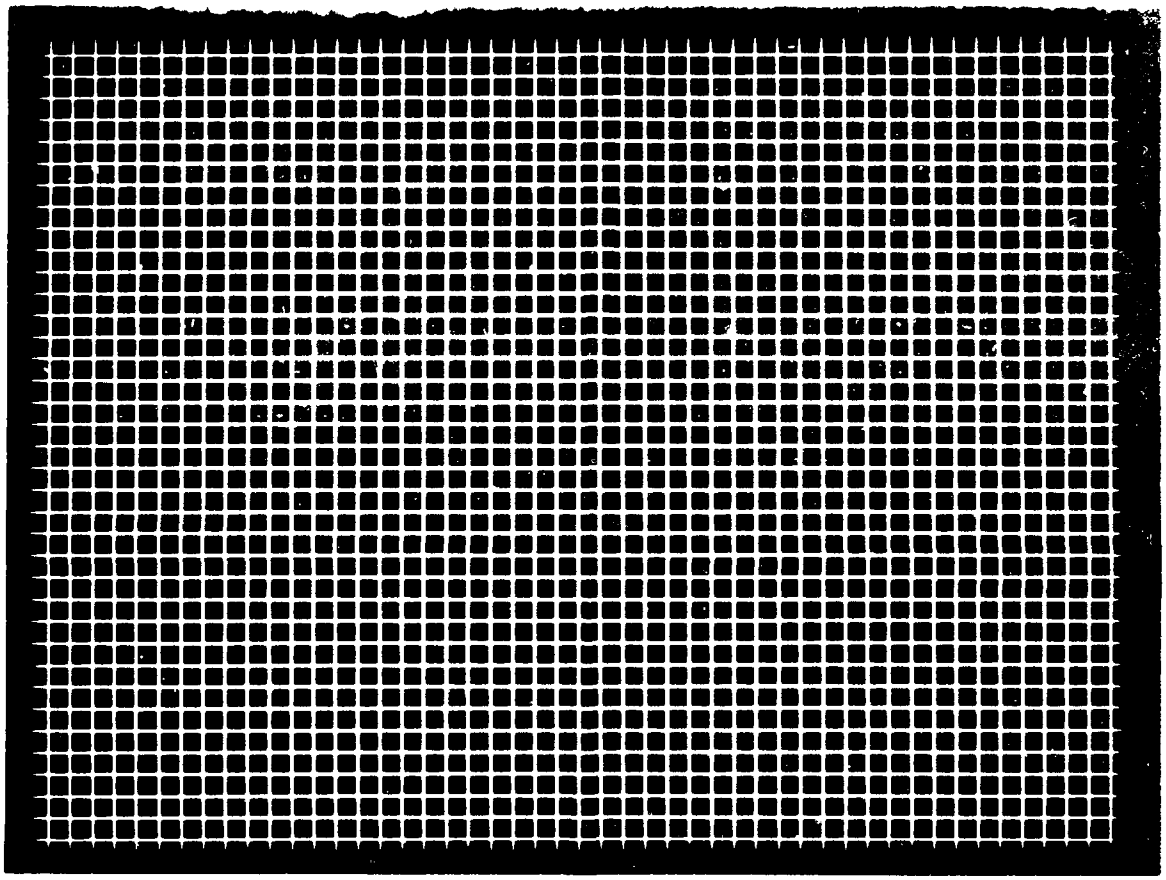


Figure 5.12 Undistorted Reference Grid Board.

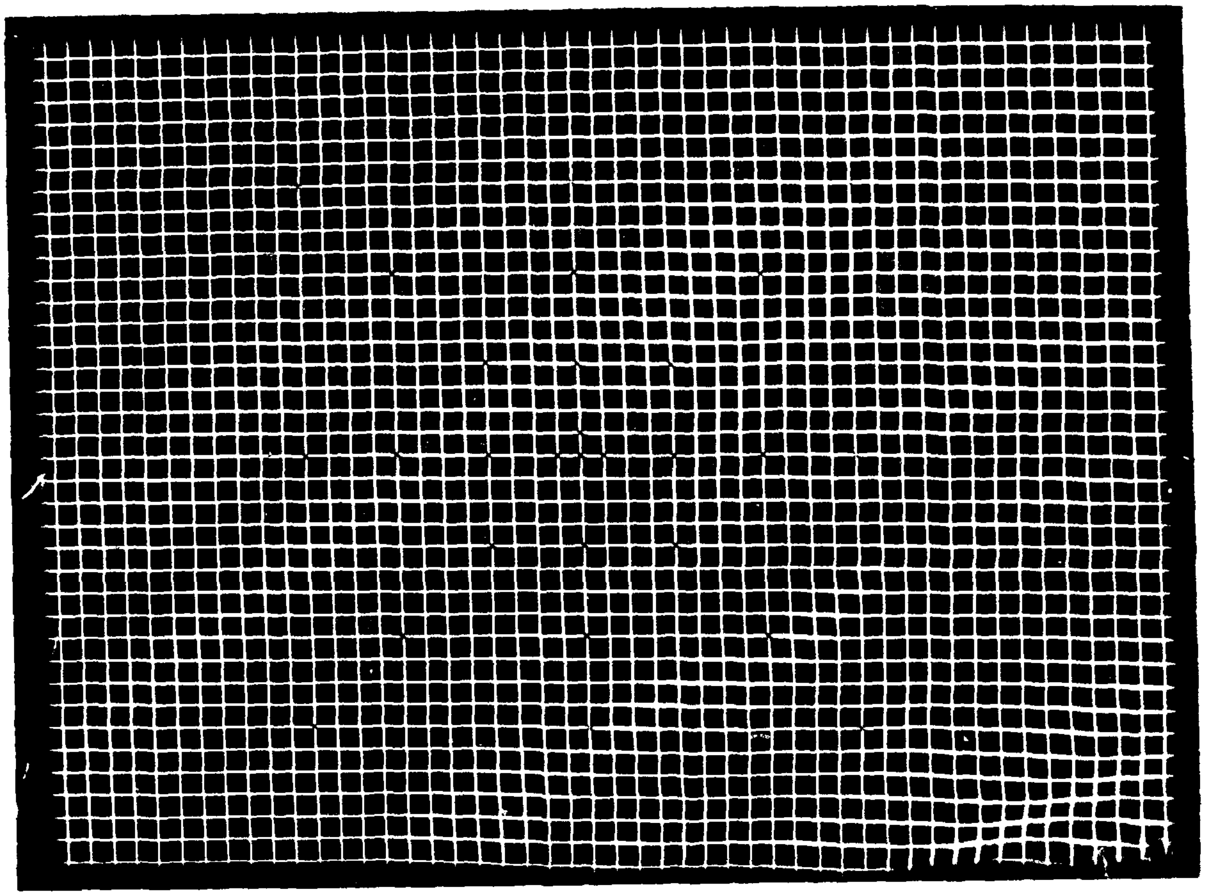


Figure 3.13. Design Eye Position, Windscreen in Place for Windscreen E-015-153.

seen to be much less than that of the previous windscreen (worst case of 25:1) and from Figure 3.4 the effect of binocular disparity is to cause relative displacement up to one half of a grid square in the grid board.

3.4.3.2 Point-by-Point Measurements

The next testing done was the point-by-point laser beam deviation measurements. The procedure was to align the laser beam to a reference point on the grid board without the windscreen in place. Then the lens was inserted and aligned, so as not to deviate the laser beam, at a distance of one focal length from the target. The windscreen was then inserted and the spot displacement noted with and without the lens in place. Figure 3.14 shows an arrow graph of the spot displacements caused by angular deviation only. The solid arrows show where the primary spots moved to, and the dashed arrows show where the secondary (ghost) spot moved to when the windscreen was inserted. It is interesting to note that the rotation of the primary spot arrows appears to be close to linear, which indicates that these deviations are due mostly to the windscreen geometry. The secondary spot arrows seem to move more eratically and even suddenly change direction in some cases. This direction change would cause the secondary image to move past the primary image, resulting in considerable viewing problems. This information containing both magnitude and direction of the spot displacements could present a reasonable evaluation of the double imaging problem. In the worst areas of double imaging, the intensity of the secondary spot was to be about one order of magnitude less than the intensity of the primary. The tertiary image was decreased by a factor greater than two orders of magnitude from the primary.

The distortion of the grid board seen in the photographs can more easily be followed in a graph of the magnitude of the angular deviation as shown in Figure 3.15. This is because a

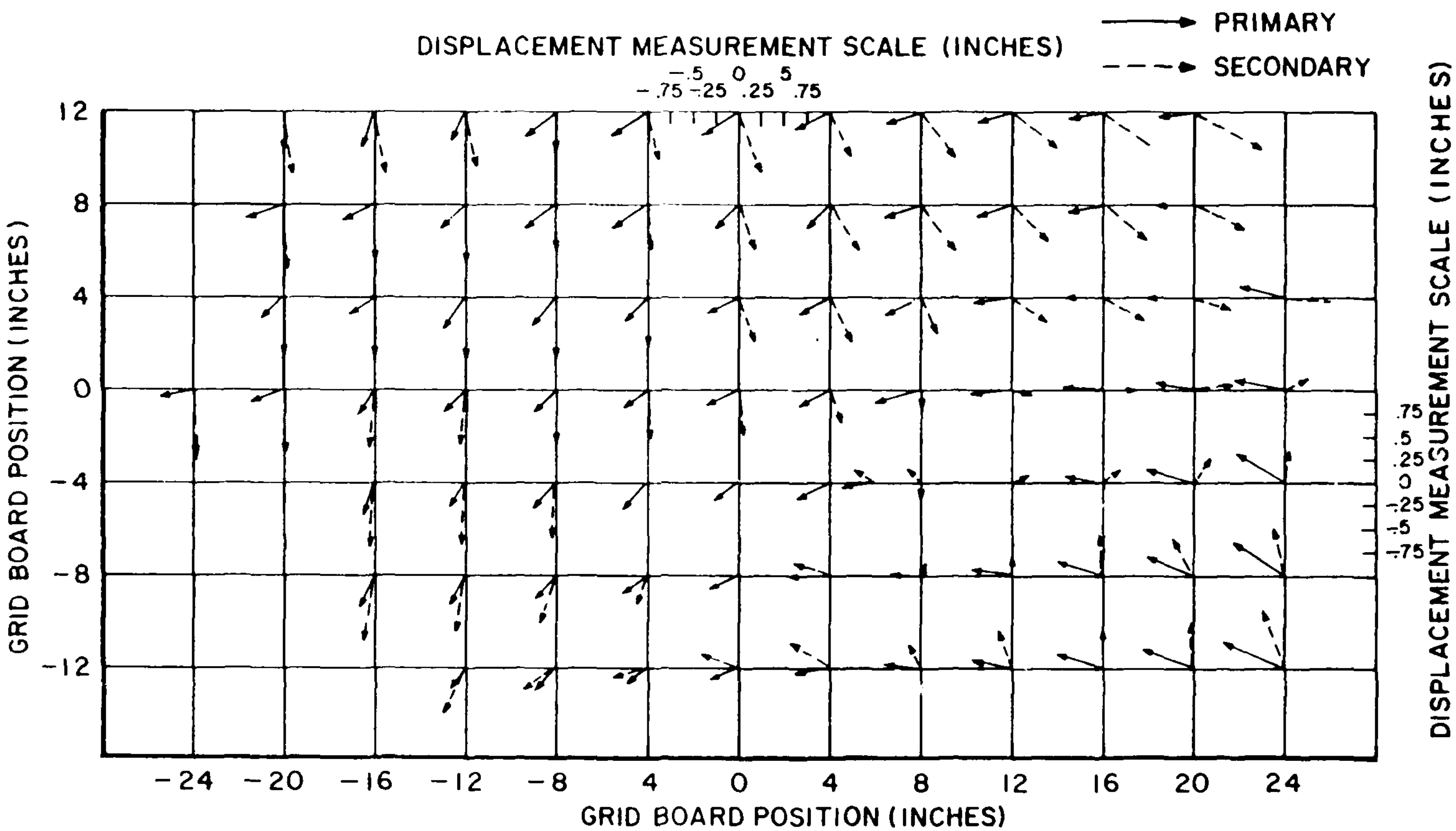
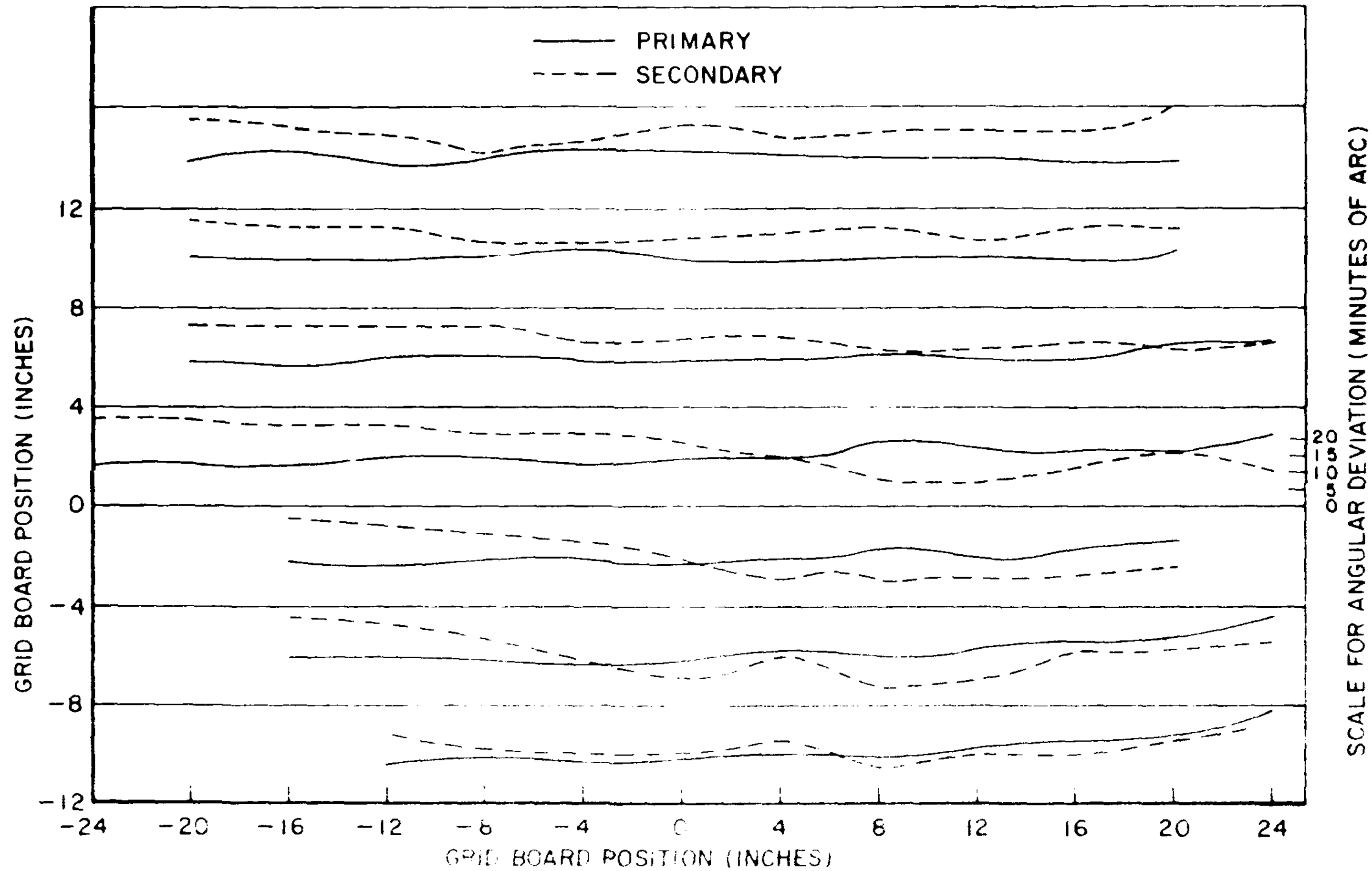


Figure 3.14. Laser Beam Displacement Caused by Angular Deviations for Windscreen E-015-153.



5.15. Laser Beam Angular Deviation (Minutes of Arc) for Windscreen E-J15-153.

uniform deviation or a uniformly changing deviation (as seen by the rotating arrows) can not be seen in the grid board photographs, which show only the area by area relative change of deviation caused by the windscreen. This is not to imply that the direction or change in direction of deviation (as shown by the arrow graph) is not important. However, no erratic or dramatically varying changes in deviation direction in the primary laser spots were seen (see Figure 3.14). As expected, the magnitude of angular deviation seen in the secondary image appears to be a function of the rate at which the angular deviation is changing. The secondary image is a product of multiple reflections within the windscreen. Therefore, the angular deviation of the secondary image is the product of reflections and refractions caused by more than one path through the material of the transparency and from more than one point on each surface.

Using the measured angular deviations and the measurements of total displacement of the laser beam (without the lens in place) the lateral displacement caused by the windscreen was calculated. The lateral displacement did not appear to vary much within the accuracy of the calculations. Small variations would be expected as the angular deviation changes, since the beam may be travelling a slightly different path through the windscreen. Figure 3.16 is a graph showing the lateral displacement versus position. It is interesting to note that the displacement of the secondary image is close to zero. The difference between lateral displacement of the primary image and the secondary image could be useful in evaluating prismatic effects (if the localized area change in angular deviation is small).

3.4.4 Grid Board Photography and Point By Point Measurements of Windscreens 157300 - 51A S/N017 and E-016-142 (F/111)

Grid board photographs of these two windscreens were taken and compared to point by point measurements. In addition to measuring the point by point laser beam deviations, the deviations as seen from the left and right eye positions were

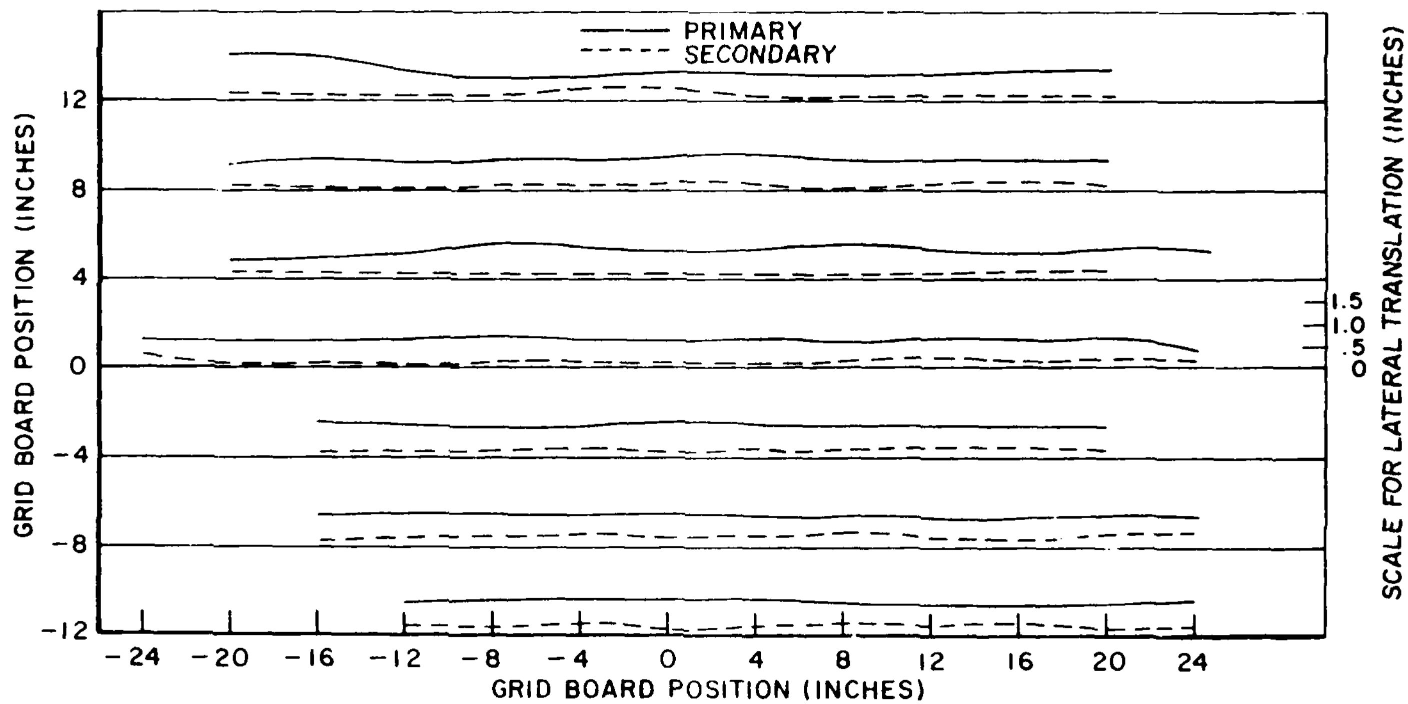


Figure 3.16 Laser Beam Lateral Displacement for Windscreen E-015-153.

mapped out. The procedure to make the binocular deviation measurements between the left and right eye was the same as that for a single beam measurement except that two parallel beams were used. The time required to make the binocular measurements was not much longer than that for the monocular measurements. However, the difficulty of the measurements increased and because of this only a limited number of points were mapped.

Grid board photographs of the two windscreens were taken at the design eye position, the left eye position, the right eye position, and double exposure from left and right eye position.

The lightweight windscreen showed very little grid board distortion. The individual photograph of the grid board showed no apparent visual grid board distortion. Figure 3.17 shows a photograph of the binocular effect for the lightweight windscreen (157300 - 51A S/N 017) using the double exposure technique. The largest relative grid board displacement was 0.125 of a single grid. This is between three minutes and five minutes of binocular disparity at the grid board.

As seen from the graphs of the *lightweight* windscreen laser beam deviation, (Figure 3.18) the deviation caused by the windscreen increases uniformly in accordance with the windscreen geometry. The lines on the angular deviation graph are, in fact, linear to within about $\pm$ 3 minutes of arc. Since the accuracy of our measurement is only $\pm$ 1.2 minutes of arc, the slight variations seen in the angular deviation graphs are not sigificant. To the same extent, the laser beam displacements caused by angular deviation (shown on the arrow graph in Figure 3.19) are very well behaved and predictable based on the windscreen geometry. The only problem encountered in testing the lightweight windscreen was in trying to locate the secondary image. Those secondary points located were within five minutes of the primary and of very low intensity. There was a fair amount of scatter present which may have partially concealed the low intensity, slightly displaced secondary image. In general the lightweight windscreen was of much better optical quality than any of the heavyweight windscreens examined.

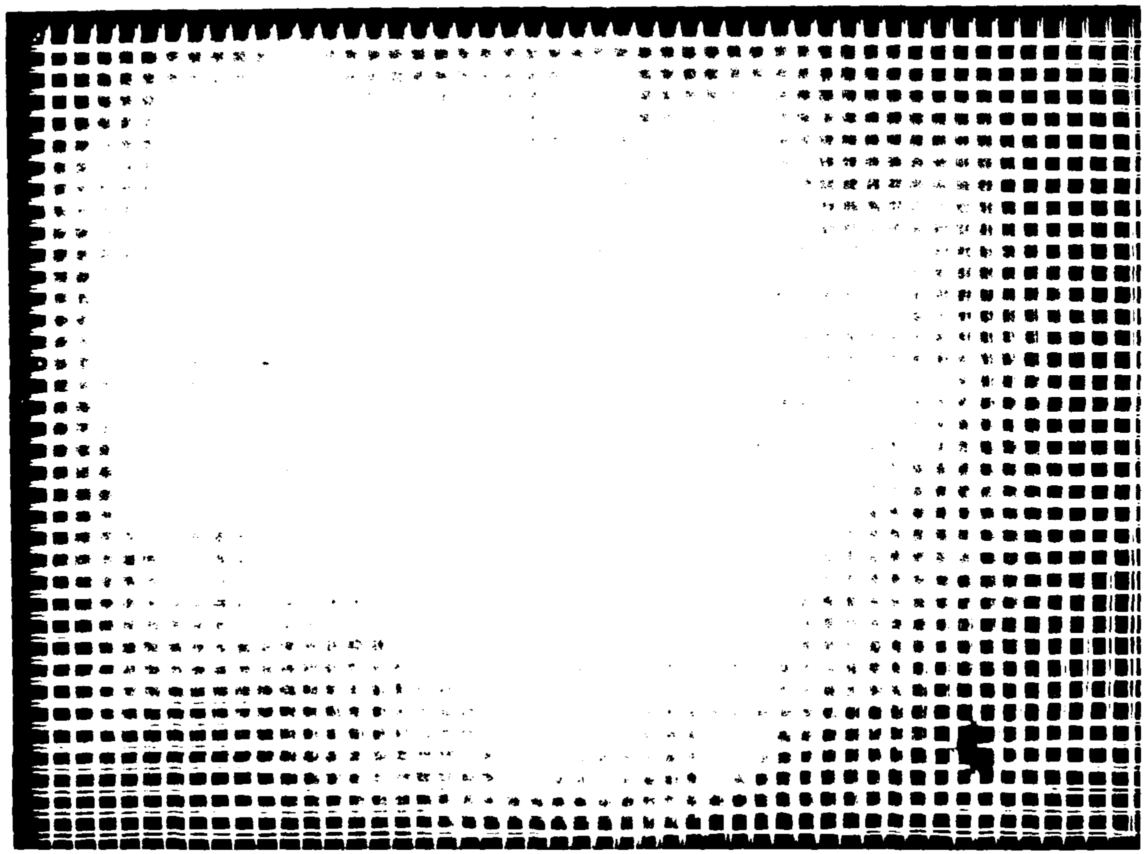


Figure 3.17. Double Exposure of Grid Board from Left and Right Eye Positions for Windscreen 157300-51A S/N 017

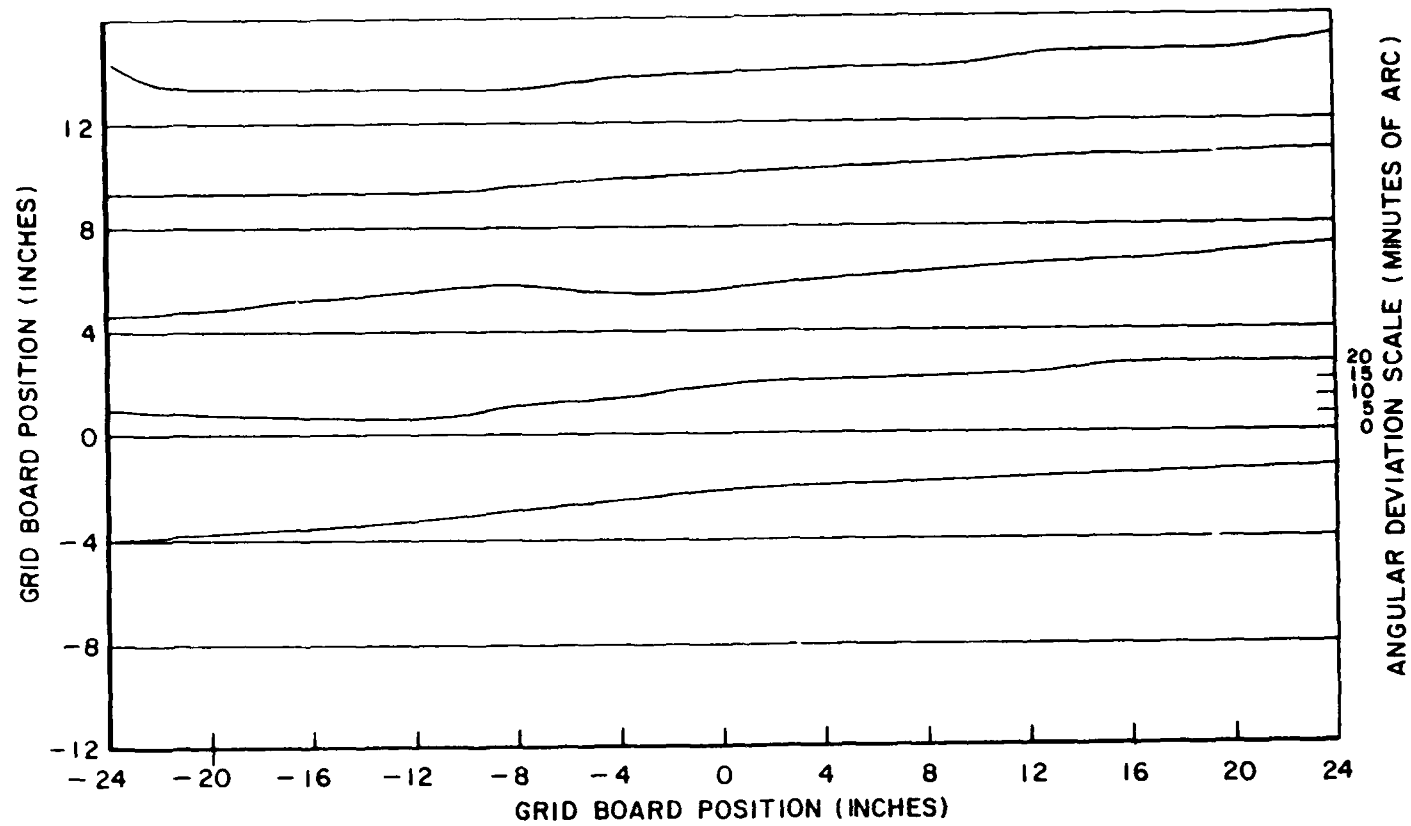


Figure 3.18. Laser Beam Angular Deviation for Windscreen 157300-51A S/N017.

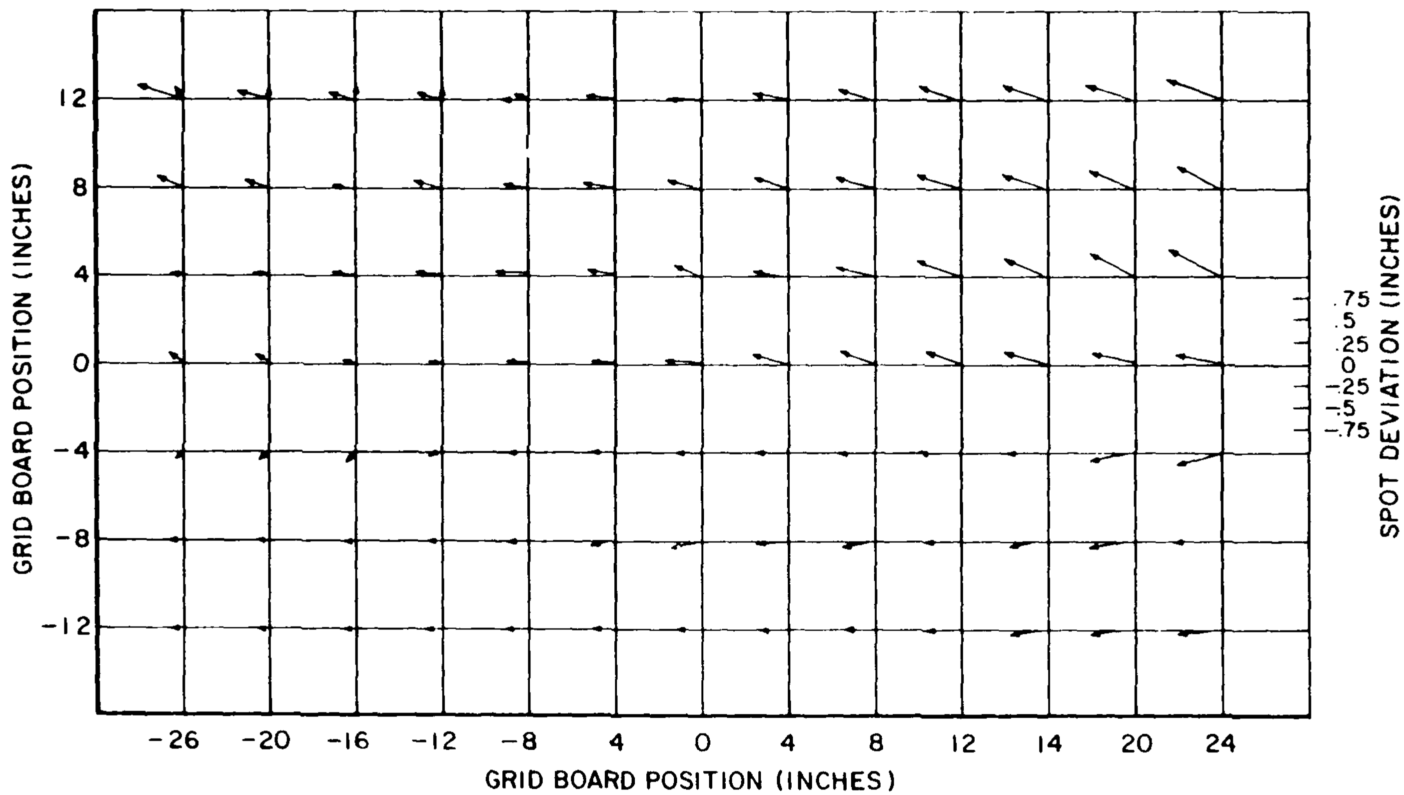
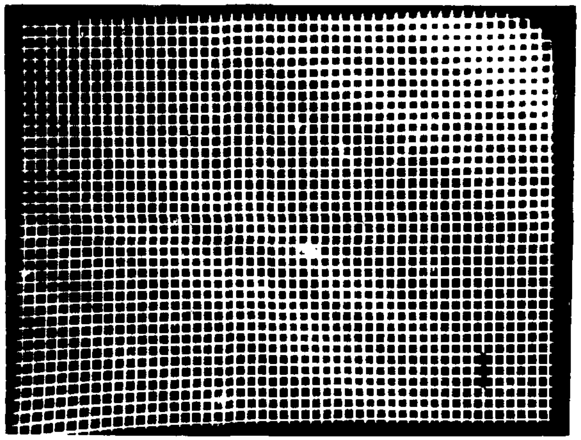


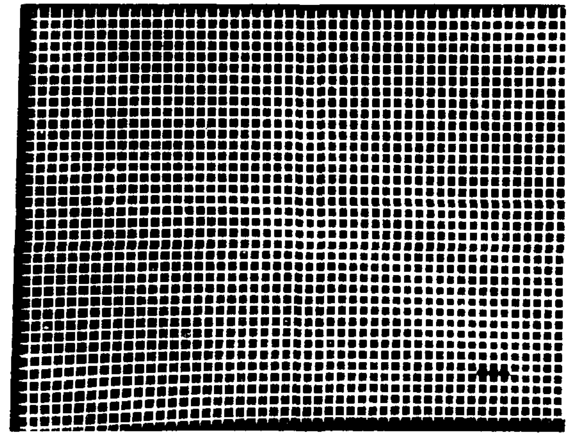
Figure 3.19. Laser Beam Displacement Caused by Angular Deviation for Windscreen 157300-51A S/N017.

The heavyweight windscreen (E-016-142) did not appear to be as good, optically, as the lightweight. The grid board was lowered to examine a lower (further forward) area on this windscreen than had been examined before. Figure 3.20 shows the grid board photographs taken from the left eye, right eye, and the left edge of the viewing area. The left edge of the viewing area had the worst grid board distortion, with a worst case slope error of 13:1. The largest binocular disparity obtained from the grid board photograph was one half of a grid or 13 minutes of binocular disparity. Although the deviations seen were not very large, they did increase significantly in the left edge of the windscreen as shown in Figure 3.21. This may have been due to the fact that the measurements were made closer to the edge on this windscreen than had been done on previous windscreens (because the forward part is narrower). A more severe problem in this windscreen may be the large and quickly varying separation between the primary and secondary images (see Figures 3.21 and 3.22). This secondary image is clearly visible in most of the windscreen.

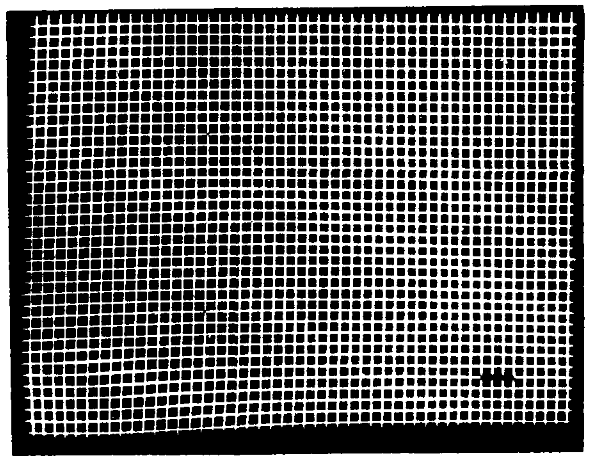
In addition to the monocular laser beam mapping, a limited amount of binocular mapping was done (Figure 3.23). The lower part of the Figure shows an arrow graph of the laser beam displacement for the left and right eye position as caused by angular deviations induced by the windscreen. Possibly a more useful measurement of the binocular disparity is the angular separation between the left and right eye laser beam deviations. A graph of this is shown on Figure 3.23 directly above the respective arrow graphs. In most cases, this angular separation for the binocular disparity in this windscreen was between 10 and 15 minutes of arc. This windscreen would probably not be acceptable because of the large binocular disparity. It is important to note that this angular separation is not constant. This effect would require a pilot to continually readjust in an attempt to fuse the two images presented from each eye.



(a) Right Eye



(b) Left Eye



(c) Left Edge of Viewing Area

Figure 3.20 Grid Board Photographs for Windscreen E-016-142

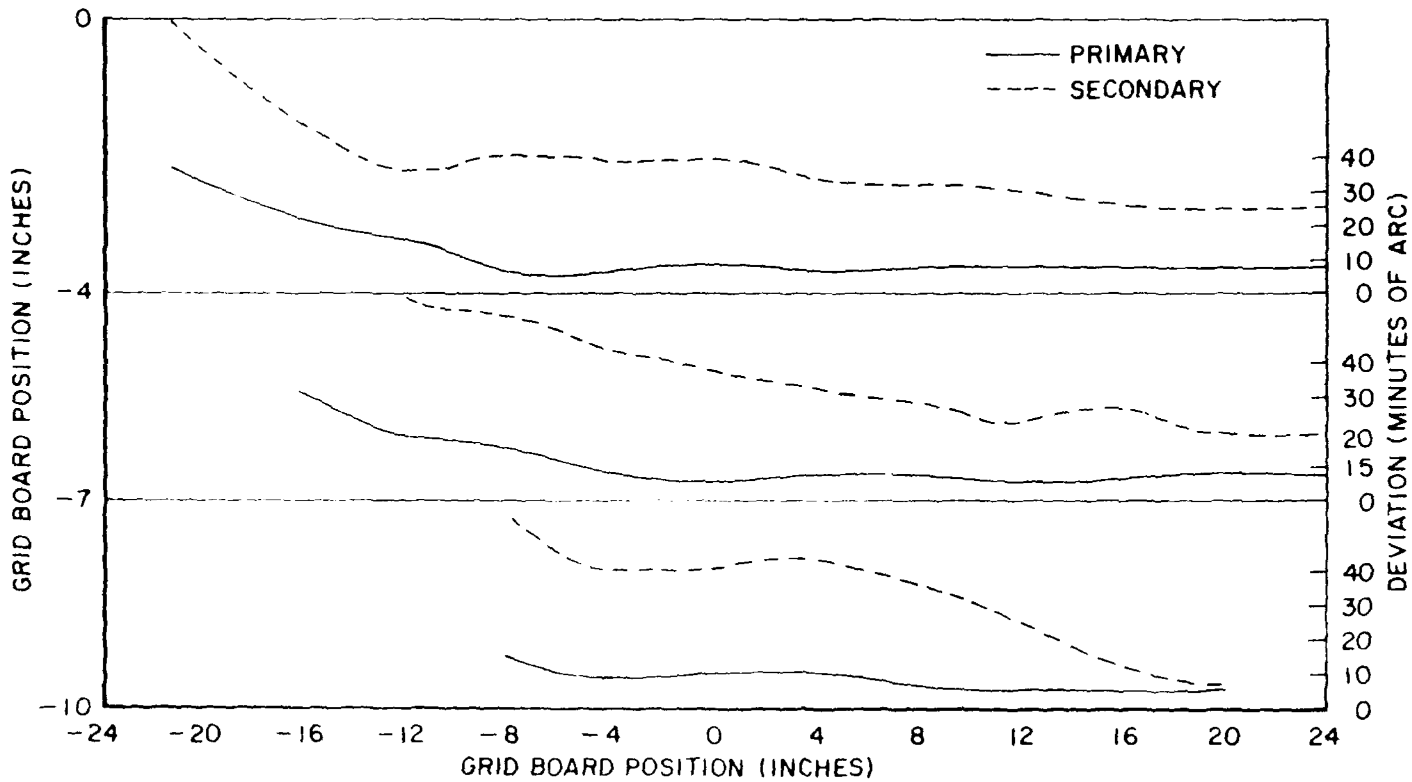


Figure 3.21. Laser Beam Angular Deviations (Minutes of Arc) for Windscreen E-016-142.

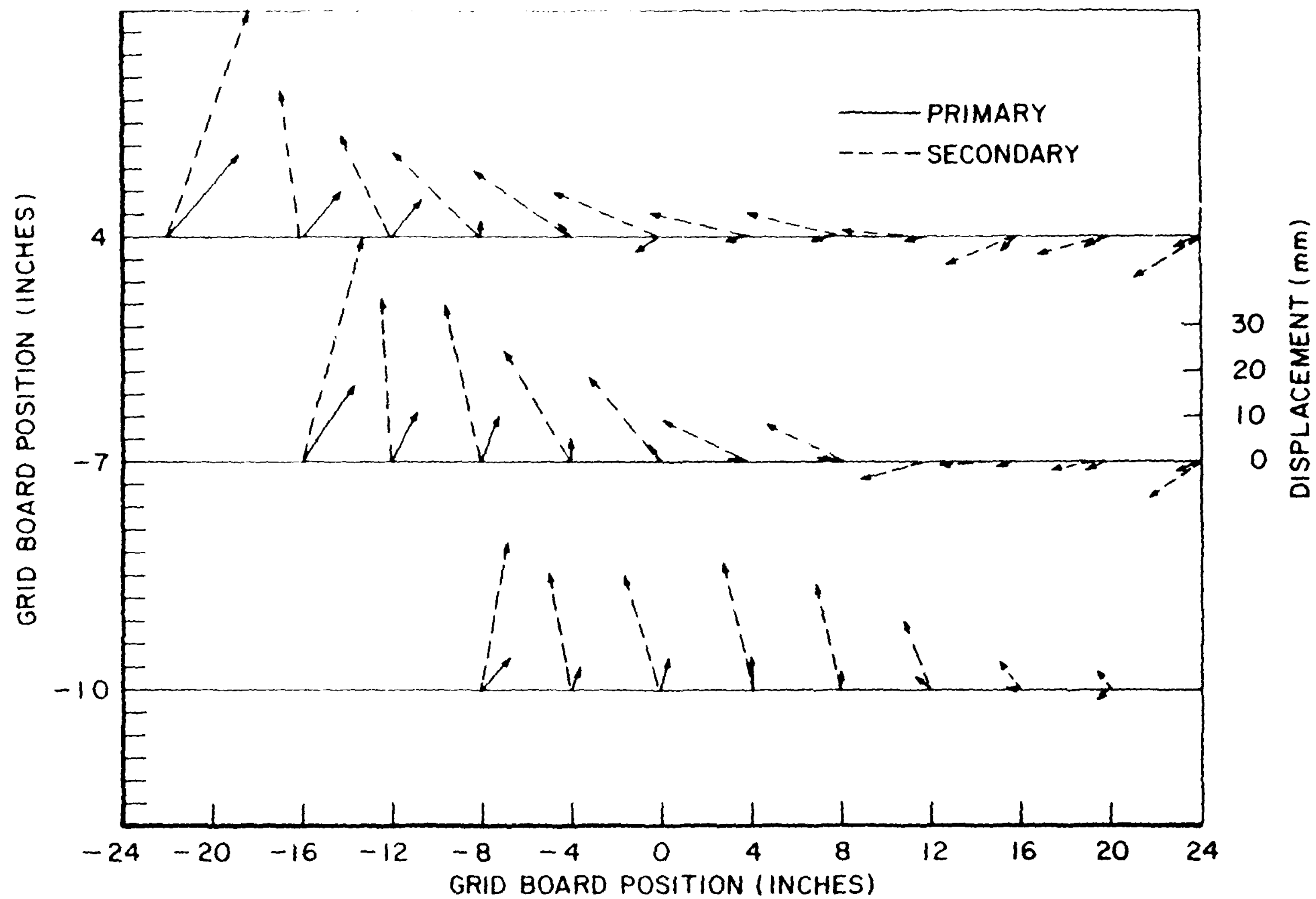


Figure 3.22. Laser Beam Displacement Caused by Angular Deviations for Windscreen E-016-142.

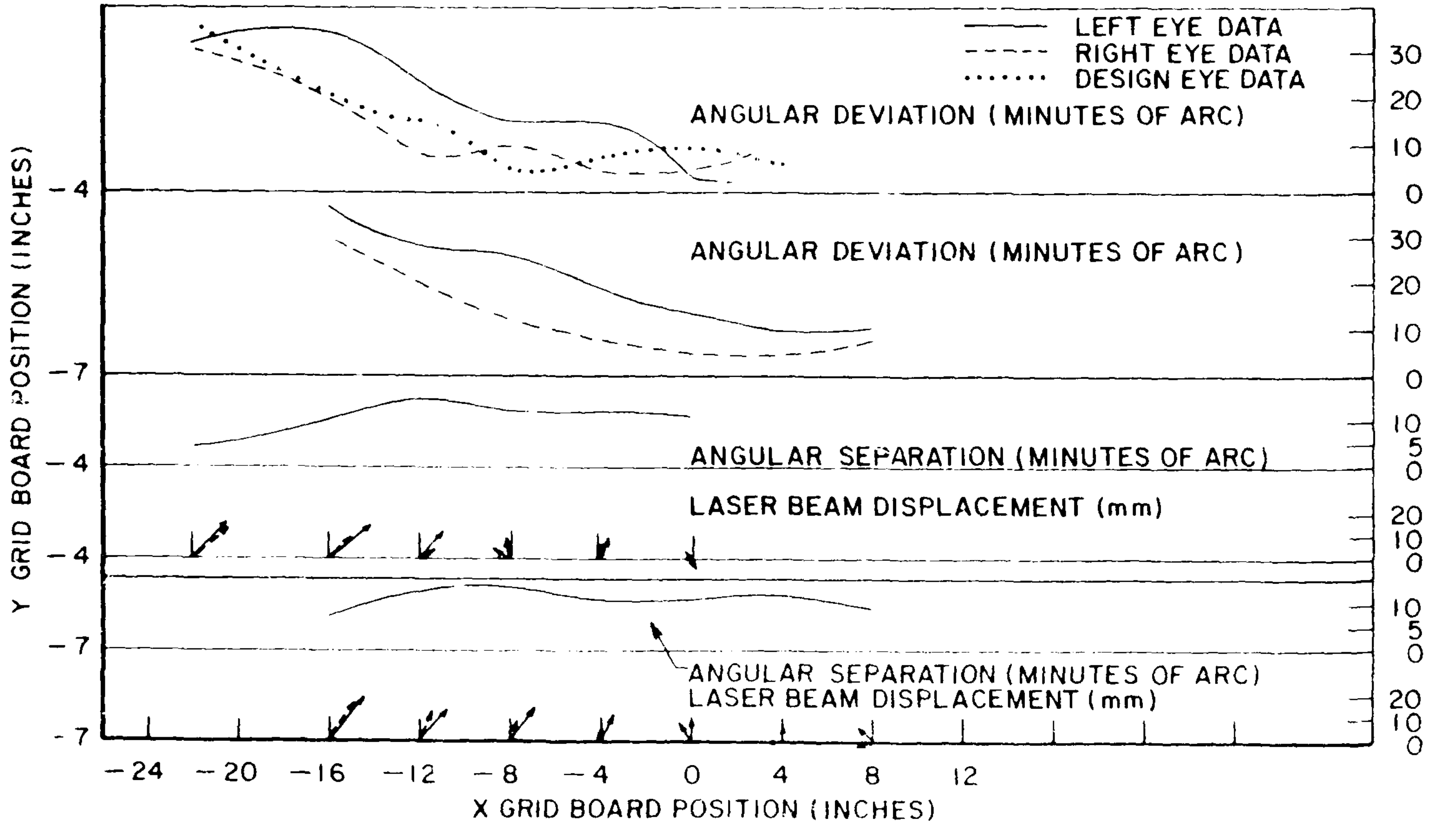


Figure 3.23. Binocular Disparity Evaluation of Windscreen for E-016-142.

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The [illegible] part of Figure 3.23 shows a graph of the angular deviation as seen from the left eye, right eye, and design eye position. The design eye position data may not be exactly correlated since it was taken at a different time. The angular deviation for the three eye positions is not greatly different, although they are displaced from each other. It is interesting to note that lensing effects can be seen more easily on this graph, in particular, the area in the negative four graph between X = -12 and X = -4. The design eye position data shows a sharp decrease in angular deviation (like the center of a lens) while the right eye position data shows an increase in angular deviation and the left eye position data is relatively constant. This actually gives data in three dimensions, from which a wave front could possibly be reconstructed and power calculated (although it is still anamorphic in character). This type of data could more easily be taken using a movable windscreen mount, rather than realigning the optical system each time.

3.5 OTHER TECHNIQUES CONSIDERED

As mentioned previously some moire techniques were tried by overlaying a grid board negative over a grid board positive. The process of making a moire by rotating the camera back between two exposures gives two positives overlayed and does not exhibit usable data. The positive-negative technique, however, does show promise of giving an overall view of the windscreen distortions and lensing.

Also attempted was single pass interferometry by using a Mach Zehnder interferometer and a shearing interferometer. Direct interferometry may be too sensitive in some areas of the windscreen when at the installed angle. Interference fringes of this type, however, do have a known high degree of accuracy. Interferometry has been studied for many years and the patterns obtained can be thoroughly analyzed with modern techniques. A double pass system would be more complicated and not as directly sensitive to the distortions we are interested in

investigating. An interesting aspect of the Mach Zehnder system is that it could be used to directly compare the lensing seen between two adjacent viewing areas (binocular effect).

Although it is not directly applicable to our present measurements, some holographic techniques were tried as well. It was found that real time holographic interferometry was sensitive to stress changes in a transparency. A similar technique could also be used to obtain three dimensional, hard copy documentation of a windscreen which could be used later for comparisons without a need to do an extensive documentation of the windscreen initially.

3.6 COMPARISON OF COST FOR WINDSCREEN TESTING TECHNIQUES

In order to compare the different techniques used to evaluate windscreen optical quality, the cost of equipment and the time to perform the different tests during our experiments will be described.

3.6.1 Grid Board Photography

For each windscreen the time to perform the required tests is:

1. 30 minutes to take the photographs (single and multiple exposure).
2. 2 hours to develop and print the photographs
3. 3 hours to analyze data where the analysis is a well defined task.

The types of equipment and cost are:

1. 3 ft by 4 ft light box, $300.
2. Simple tape grid board, $100.
3. Simple windscreen mount, $200.
4. Used 4 x 5 Gruflex camera, $200
5. Heavy duty tripod, $850.
6. One set of film and supplies, $100.

The total cost of equipment was $1750 and the time to evaluate each windscreen was about 5.5 hours.

3.6.2 Point-By-Point Laser Deviation Measurements

In evaluating the laser beam deviations during this program it was found that the time required to measure 10 different points was one hour. For mapping a windscreen on 4 inch centers, 7 hours are required and it is recommended that 3 times this data be taken for a total of 21 hours. Data analysis with a computer required about 4 hours for each 50 points.

The type of equipment and cost are:

1. 5 mw HeNe laser, $700.
2. Two tripods, $1200.
3. 6 inch diameter lens and mount, $750.
4. Simple windscreen mount, $200.
5. Other equipment, $50.

The total cost of equipment was $2900 and the time to adequately evaluate each windscreen was 24 hours. This system was the most versatile used.

3.6.3 Point-By-Point Measurements Using a Telescope

The time to adequately evaluate each windscreen is the same as that using the laser deviation techniques of section 3.6.2, i.e., 24 hours.

The type of equipment and cost are:

1. Viewing telescope, $200.
2. Tripod, $500.
3. Simple windscreen mount, $200.
4. Target and other equipment, $50.

Angular deviation measurements are not directly readable unless a collimated source is substituted for use as an object. The cost of the equipment for reading total deviation is $1000,

and the cost increases to about $2000 if direct angular deviation measurements are required. This system provides high accuracy, but it is more difficult to operate than a laser deviation measurement system.

3.6.4 Pass-Fail Laser Deviation Measurement

This is a system similar to that described in section 3.6.2, except that it is only able to determine if any single deviation measurement exceeds a specified tolerance. Total cost is $2000 -$2500 and the time for evaluation of each windscreen is reduced to about 20 hours.

SECTION 4

NEW TECHNIQUES FOR WINDSCREEN TESTING

As part of this program new test procedures were developed for assessing the optical quality of aircraft transparencies. The Air Force specified that this work would be directed toward approaches that could quantify binocular effects. As described in the study and experimental evaluation in sections 2 and 3, the binocular effects are obtained by measuring and comparing the windscreen optical quality at the right and left eye positions. Any technique using a laser beam to obtain a point-by-point mapping of the windscreen optical quality from both eye positions will permit evaluation of binocular effects or binocular disparity.

Previously, point-by-point measurements using alignment telescopes and collimated probe beams have been very time consuming, because in order to map the windscreen deviation the windscreen is moved between each measurement. With this approach many hours are required to evaluate a single windscreen. In the study of new techniques it was decided that the mapping should not be done by moving the windscreen, but by mechanically scanning a probe beam over the windscreen.

4.1 FAST SCANNING TECHNIQUES AND REQUIREMENTS

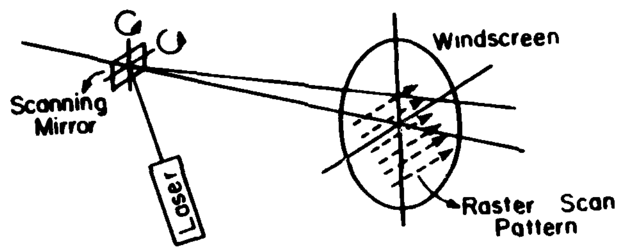
The purpose of the fast scanning systems is to provide a way that windscreen transparencies can be scanned and evaluated on a point-by-point basis at a fairly high rate of speed. The systems considered were required to use a scanning mirror system located at the design eye position to simulate a diverging beam eminating from the design eye position, or to use a scanning mirror system and source "lens" to simulate a converging beam to the design eye position. Of the different ideas developed two

were set up in our laboratories for evaluation. One technique uses a retro-reflecting screen, and the second uses a holographic lens.

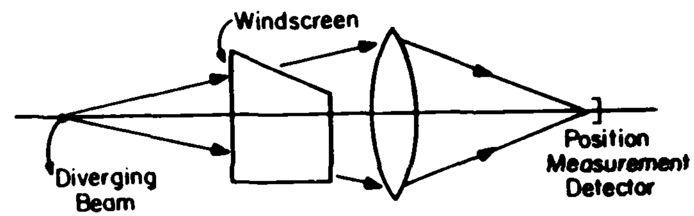
4.1.1 Retro-Reflecting Screen Technique

This system uses a scanning mirror system located at the design eye position and a retro-reflecting screen. By scanning an unexpanded laser beam in both elevation and azimuth, it is possible to simulate a diverging beam eminating from the design eye position. By using an unexpanded laser beam rather than an actual diverging beam, it is possible to make accurate measurements of the beam deviation at many distinct points on the windscreen. Depending on the different forms of the system, it is possible to measure total beam deviation, lateral displacement, and angular deviation.

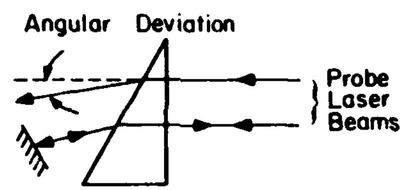
Figure 4.1a shows an unexpanded laser beam being raster scanned over a windscreen. The problem is how to measure the deviation of the beam after it passes through the windscreen. Because of our interest in techniques that are faster, a system is not allowed where a detector is moved over the windscreen to map the laser beam deviations. Because of this it is necessary to re-image the scanning beam onto a single detector. One approach would have been to use a large lens such as that shown in Figure 4.1b, but instead a technique was developed where this lens is replaced by a large retro-reflecting screen. The University has used these screens in our work with stroboscopic holographic interferometry[29,30] and it has been very useful because of its high reflectivity. Such a screen will retro-reflect 30 percent of an incident collimated laser beam into a three degree solid angle, i.e., a three degree divergence will be introduced into the incident collimated laser beam. Figure 4.1c shows another consideration in the design of the system where the effect of a glass wedge (windscreen error) on an incident laser beam is shown. As shown in Figure 4.1c the angular deviation



(a) Raster Scanning Technique



(b) System With Lens



(c) Retro-Reflection Consideration

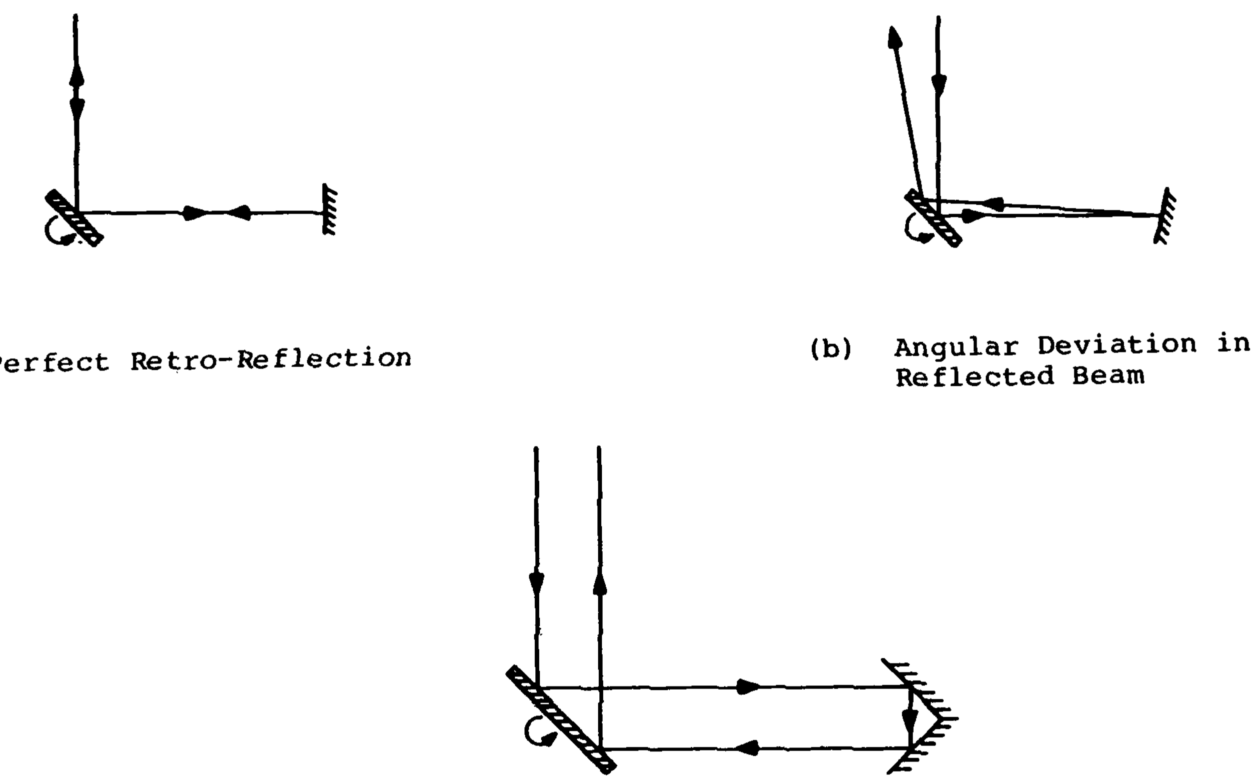
Figure 4.1. Fast Scanner System Considerations.

errors introduced by the wedge is eliminated if the beam is retro-reflected back through the glass wedge. Because of this effect the scanning laser beam after retro-reflection cannot be allowed to pass back through the windscreen.

The principle of the system is then to scan an unexpanded laser beam from the design eye position, to simulate a beam diverging from the design eye position. After this beam goes through the windscreen, is retro-reflected and directed by a beam splitter around the windscreen, it converges to a point conjugate to the scanning at the design eye position. If the beam deviations are measured at this "image" the total deviation of the windscreen can be mapped out. However, if this point image is relayed back and reflected off the scanner, the beam can be analyzed for any angular deviations or lateral displacements caused by the windscreen.

Figure 4.2 shows a laser beam incident on the scanner, reflected to a retro-reflecting surface, and reflected back to and from the scanner. Laterally displaced beams will be parallel but displaced to the incident beam while angular deviated beams will be reflected at an angle to the original beam from the laser. Thus, lateral displacements can be measured by beam displacement and angular deviation can be obtained using a focusing lens as described in section 3.

Figure 4.3 shows a schematic drawing of the system used for evaluation of this technique. Only a single axis scanner was used, and polarizing beam splitters and retardation plates maximized transmission or reflection of the probe beam while eliminating spurious signals from unwanted reflections by the various optical surfaces in the system. In this system the unexpanded laser beam is directed by the scanning mirror to scan in only one plane. The beam then goes through a polarizing beam splitter located directly after the scanner. The beam was previously made to be horizontally polarized, so that close to 100 percent will be transmitted directly through the cube.



(a) Perfect Retro-Reflection

(b) Angular Deviation in Reflected Beam

(c) Lateral Displacement in Reflected Beam

Figure 4.2 Use of Two Reflections Off the Scanner to Separate Angular Deviation and Lateral Displacement.

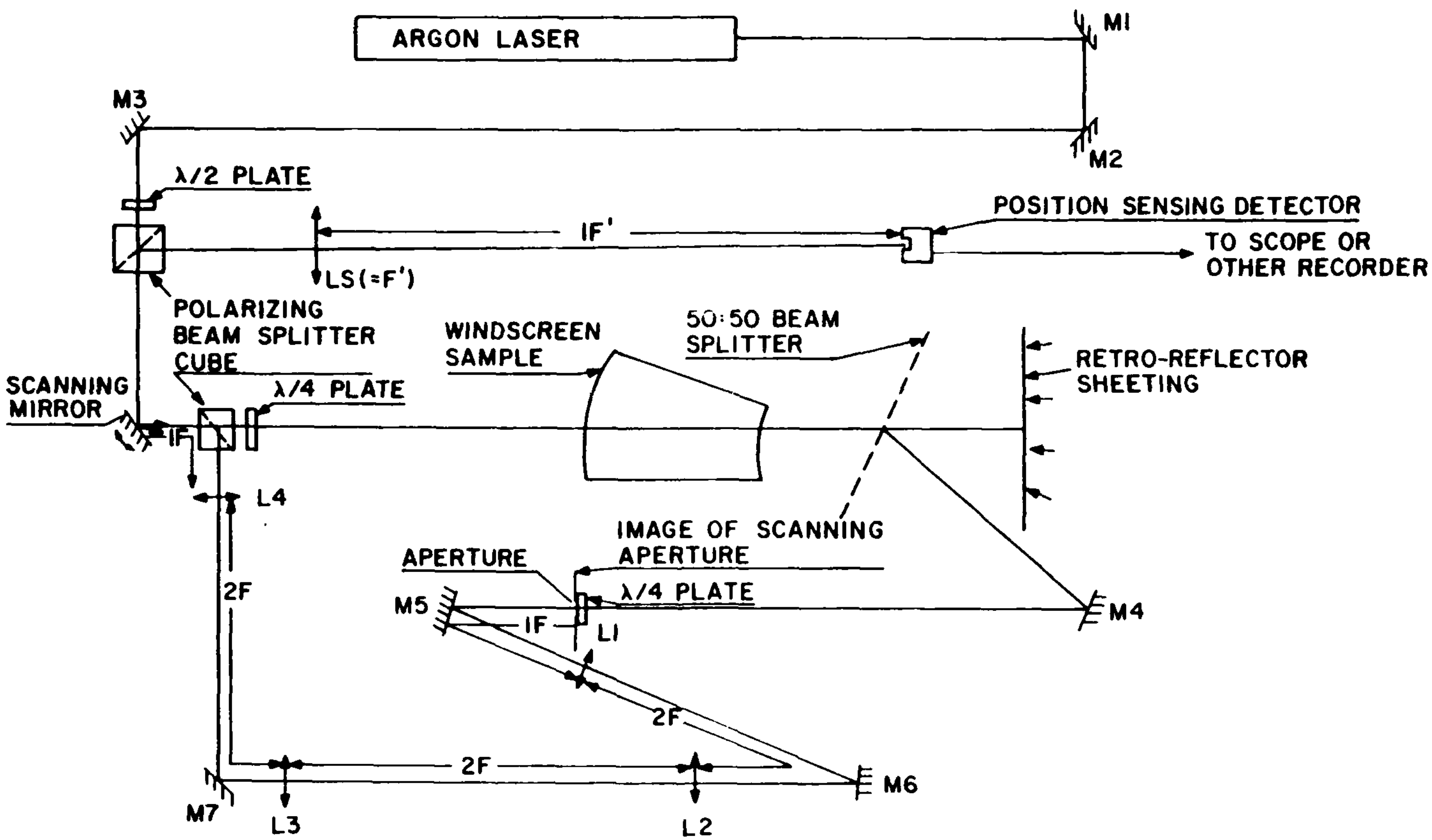


Figure 4.3. Fast Scanning Optical System.

Directly after the cube, a quarter waveplate renders the laser beam circularly polarized. This beam then goes through the transparency sample. After the transparency, the beam goes through a 50:50 beam splitter (where part of the beam is lost) and to a retro-reflecting screen, which directs the beam back to the 50:50 beam splitter along its original path. The component which goes back through the windscreen will be rendered vertically polarized by the quarter wave plate and will be reflected off to the side by the polarizing beam splitting cube. The component reflected from the 50:50 beam splitter will be directed to an aperture which is the image plane of the scanner. At this plane the beam will be pivoting around a point. A possible option for this system would be to put a second scanner at this point, precisely syncronized to the motion of the first scanner. This would remove the motion induced to the beam by the first scanner and allow the beam to be evaluated for angular deviations caused by the windscreen sample without the need for any further relay optics (or the polarizing beam splitter). A second scanner of this type was not available to us at this time. This aperture plane is, therefore, relayed back (by means of lenses L1 through L4, a one-to-one, afocal system), through the polarizing beam-splitting cube, to the original scanner. A second quarter wave plate at our image plane has made the beam vertically polarized so that the polarizing beam splitting cube will reflect the beam back through the scanning mirror system. Since the plane of polarization of the beam has been rotated 90 degrees to the initial incoming beam, we can use a second polarizing beam splitting cube to direct the return beam to the side to a detector system so that it can be evaluated for angular deviations caused by the transparency.

If the system is properly aligned, when there is no transparency in place, the output beam (directed to the detector) will not move when the scanner is turned on; it will be completely compensated. The alignment of this system is very sensitive. If the image plane at the aperture is not correctly

relayed back on to the scanner the motion of the scanner will not be compensated. If the magnification of the optical relay system is other than one, there will be a magnification factor to consider in measuring the angular deviations.

An important limitation to consider in setting up this system is the field of view limitation caused by the various apertures in the system. The beam splitting cube should be located close to the scanner so that the cube's diameter will not limit the scan field. The field of view will then be limited by the f-number of the relay lenses. Another problem is the diffusing nature of the retro-reflection screen. If the aperture at the image plane is made small compared to the light field coming from the retro-reflecting screen, a lateral displacement of the beam (by the transparency) will not be seen as a lateral displacement but rather will appear as an angular deviation (since the aperture is now seeing another part of the solid angle of the beam from the retro-reflecting screen). This must be taken into account when making the measurements of angular deviation caused by the transparency. This beam may also be apertured by the relay lenses at their edges. It would be advisable not to use the extreme edges of the lens since there tends to be a certain amount of "roll-off" at the edges. This would cause the beam to be bent a little more than it should be at each lens, resulting in an additive error.

Assuming proper alignment of the system, the limit of accuracy of the angular deviation caused by the transparency is caused by the focal length of the final focusing lens (lens L5). Assuming a precision in measuring the focus spot position of $\pm$ 1/16 inch and focal length of 90 inches, gives an accuracy of better than $\pm$ 2.3 minutes.

A sample of a lightweight windscreen was evaluated using this system. One problem observed was that the lateral displacement induced by the sample (set at 45 degrees, 22 inches from the

scanner) appeared as a constant angular deviation offset in the data. This offset was approximately 12 to 13 minutes of arc. The data was compared to deviation measurements made by just putting an unexpanded laser beam through the sample, at the same points, and measuring the angle of the deviated beam directly after the sample (over a 90 inch distance). The absolute angular deviation caused by the sample ranged from 5 minutes of arc to 9 minutes of arc. These measurements were made directly without the scanning system. The offset measurements made with the scanning system ranged from 17 minutes of arc to 23 minutes of arc. Taking into account the 12 to 13 minutes of arc offset caused by the constant lateral displacement, the point-by-point measurements made with the fast scanner system agreed with the point by point direct angular deviation measurements to within 2 minutes of arc as shown in Table 4.1.

TABLE 4.1 COMPARISON OF DIRECT MEASURE AND FAST SCANNING DATA

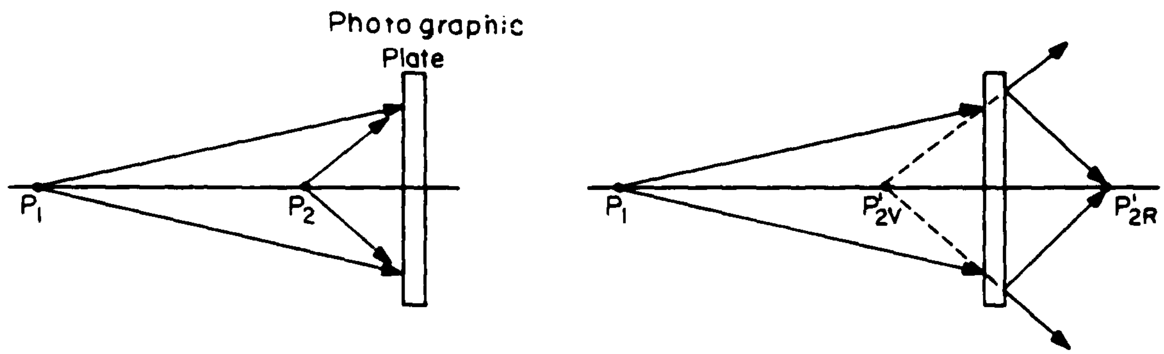
Point	Direct Measure	Fast Scanner	Offset
1	5 (minute of arc)	17 (minutes of a arc)	12 (minutes of arc)
2	5	17	12
3	5	17	12
4	9	23	14
5	8.5	21.5	13

These measurements are repeatable to less than 2 minutes of arc. This sets a practical limit on the current system of ± 2 minutes of arc. The constant angular deviation offset was produced by the long focal length lens used for measuring angular deviation. Since no position measurement detector array was available, all the deviation measurements were made visually. To get the largest displacement possible for a given angular deviation error, a 90 inch focal lens was used. This lens was not able to form a real image of the retro-reflecting screen and this introduces an offset in the measured angular deviation data. With an 80 inch separation of screen, a lens with a focal length of 40 inches or less should be used.

4.1.2 Holographic Lens Technique

This system was developed as a second approach to a fast scanning technique. A holographic scanning system is very useful in the case where a reference windscreen exists as a standard of comparison for the test windscreen. The holographic approach is simpler than the retro-reflecting screen approach because all the lateral displacements produced by the windscreen geometry are not observed in the laser probe beam. A holographic system could also simplify binocular measurements because it could reconstruct both the right eye and left eye images at one time.

Work on holographic optical elements is now an active research area. The interest in them has been for full aperture lenses[31] and as elements in optical scanning systems[32]. Their operation is conveniently understood in terms of the image properties of a simple Fresnel zone plate. One type of holographic lens is made with two point sources on the same side of the photographic plate as shown in Figure 4.4a (transmission hologram 5). When the hologram is illuminated by the point source P_1 two



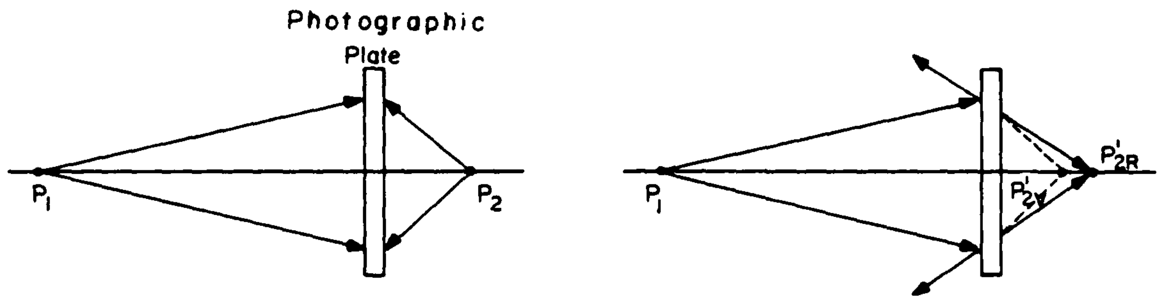
(a) Production of Holographic Lens

(b) Reconstruction of Holographic Lens

Figure 4.4. Transmission Holographic Lens

wavefronts are reconstructed (Figure 4.4b). One of the reconstructed wavefronts diverges from the virtual image P_{2V}' and the second wavefront converges to the real image P_{2R}'.

A second type of holographic lens (volume hologram[33]) is made with the two point sources on opposite sides of the



(a) Production of Holographic Lens

(b) Reconstruction of Holographic Lens

Figure 4.5 Volume Holographic Lens

photographic plate. Figure 4.5a shows the recording geometry of the volume hologram and Figure 4.5b shows the two reconstructed images when the hologram is illuminated by P_1. In the normal use of a reflection hologram only the virtual image is used because of its high efficiency. However, there is a real image $P_2{'}_R$ formed on the same side of the hologram as the original point source P_2. The real image is shifted by a small distance away from the hologram from the original point P_2. In the use of a holographic lens in a scanning system, a raster scanned unexpanded laser beam is used to irradiate the hologram from the point P_1 of Figure 4.4 or 4.5. Thus the raster scanned beam will be imaged from the scanned point on the hologram to the real image $P_2{'}_R$. For windscreen testing this permits a very convenient way to scan a laser probe beam over a windscreen without moving the windscreen.

For this program the usefulness of the real image from a volume hologram was of interest. The reason is that when a reference windscreen exists, a very useful system can be developed for measuring the deviation errors of windscreens without being bothered by the large lateral displacement introduced by the windscreen geometry. As was shown in section 3, a 25 mm thick windscreen will introduce 1.5 mm lateral displacement at 10° angle of incidence, 9.12 mm at 40° angle of incidence, and 48.6 mn at 70° angle of incidence. Ten minutes of deviation error in a windscreen produces 1.94 mm deviation in 1 meter. Since the deviation errors associated with the F-111 windscreen tested during the program were less than 40 minutes, a small linear array could be used to measure and map the deviation errors over a windscreen if compensation for the lateral displacements due to windscreen thickness is done. The way in which the system would work is shown in Figure 4.6. A large diameter volume holographic lens would be made as shown, in Figure 4.6 where two point sources

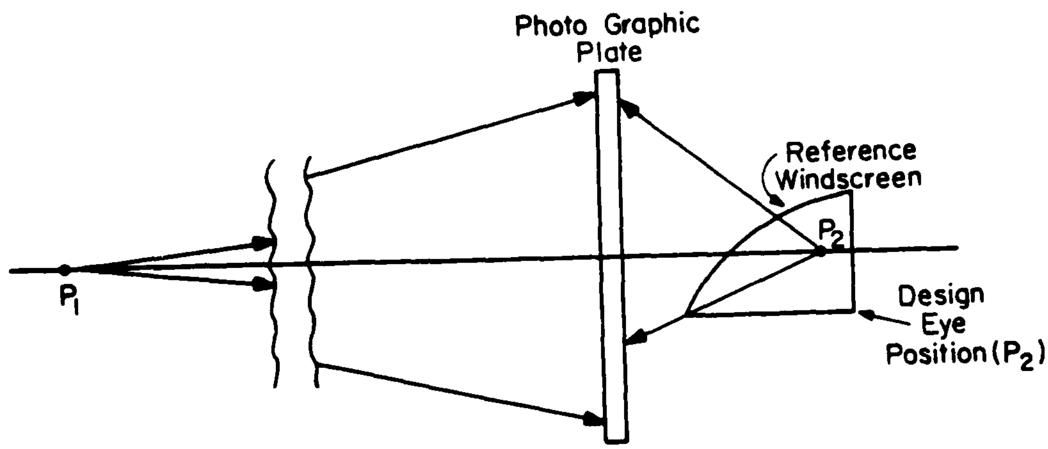


Figure 4.6 Production of Holographic Lens

are used to illuminate the photographic plate. In reconstruction the light to P'_{2R} will be displaced further from the hologram than the point P_2 when the light from P_1 is used to scan the hologram. This shift is small and could probably be neglected. If necessary the hologram could be shifted away from the windscreen to position P'_{2R} exactly on the design eye position. The deviations of the windscreen would be measured as the laser beam is raster scanned over the holographic lens. The scanning would be done to diverge from the original point P_1 and the deviations measured with the test windscreens substituted for the reference windscreen. The system accuracy can be determined and checked by taking the measurements with the reference windscreen.

Since the holographic lens is made with a windscreen in place there will be no lateral displacement effects observed in the reconstructed image at P'_{2R}. The only deviations observed will be produced by difference in deviation introduced in the probe beam between the reference windscreen and the test windscreens.

4.1.2.1 Experimental Evaluation of Volume Holographic Lenses

The work on this task was directed at making a volume holographic lens with two point sources and evaluating its imaging characteristics as it is scanned with a 2 mm-diameter HeNe laser beam. The holographic lens was made using the geometry of Figure 4.5a, and Figure 4.7 shows the details of the experimental setup used. In reconstruction a laser beam was raster scanned over the hologram with scanning mirror located at the position P_1 in Figure 4.5b. The image at P'_{2R} shown in Figure 4.5b was evaluated as the unexpanded laser beam was scanned over the hologram. In the hologram that was made the points P_1 and P_2 were 72 inches and 16 inches from the 8 by 10 inch photographic plates. In reconstruction the image P_{2R} was 17.7 inch from the hologram. Although the image at P'_{2R} is aberrated when a spherical wave is used to illuminate the entire

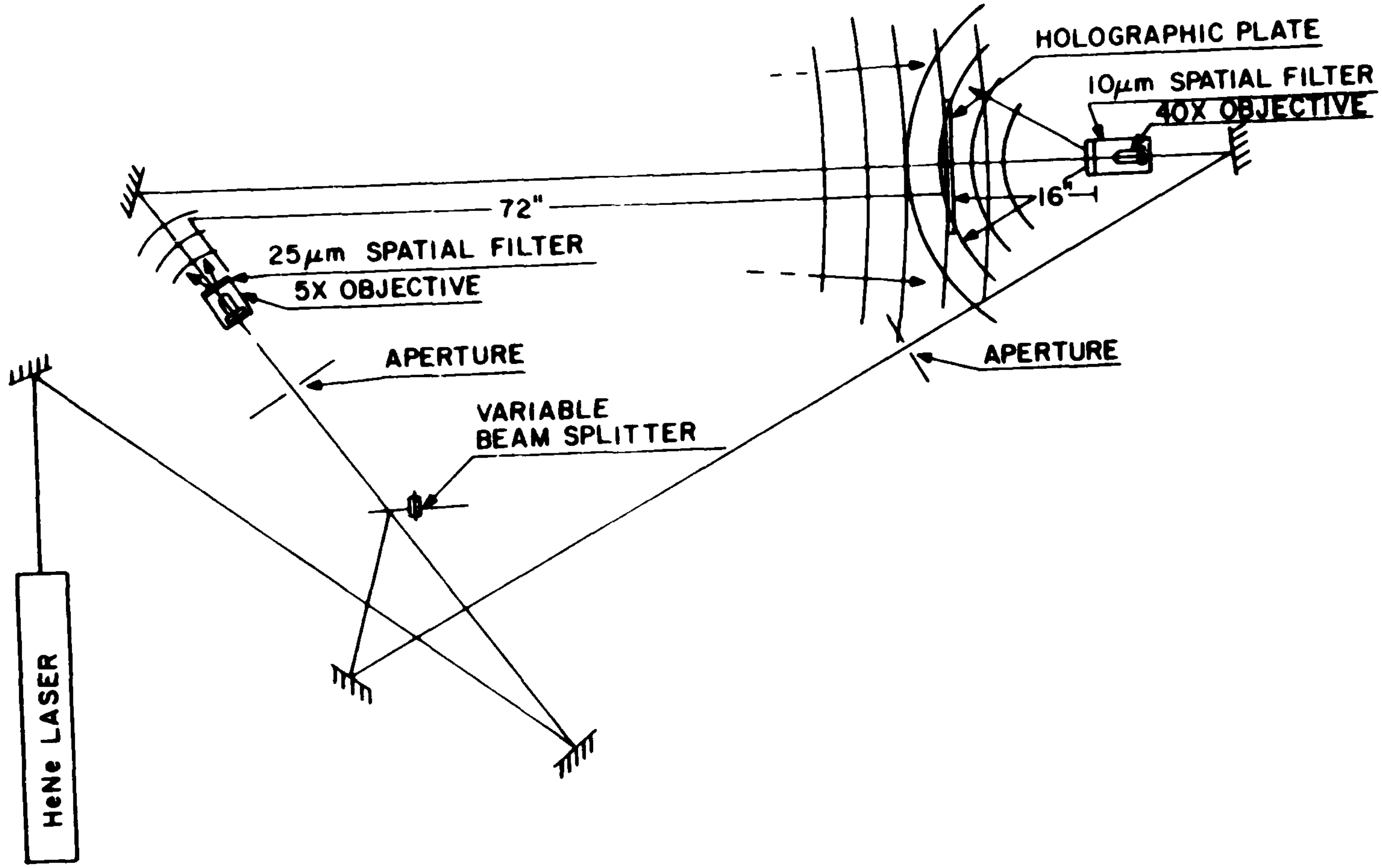


Figure 4.7. P.oduction of Holographic Lens.

hologram, the image is very acceptable from any 2 mm areas on the hologram as the laser beam is raster scanned over the hologram. The original object at P_2 was a 10 μm diameter pinhole, and the aberration effects are not significant in the large diameter images at P'_{2R} produced by the 2 mm diameter raster scanned HeNe laser. Figure 4.8 shows a multiple exposed photograph of the image at P'_{2R} and the laser beams used to scan the holographic lens for two orthogonal scans of this hologram. The hologram was not scanned at its center so both the image P'_{2R} and the laser beam used to illuminate the hologram could be recorded on one photograph. A ruler with 0.1 inch horizontal and vertical grid was placed in the image plane P'_{2R}. From the photograph the area scanned by the laser beam was 10 inch by 9 inch. The diameter of the multiple exposed image was less than 0.2 inch, and no noticeable motion was observed in the image as the laser probe beam was scanned over the holographic lens.

In order to use this system in evaluating windscreens, it would be necessary to make holograms with diameters up to 3 ft in diameter. Such large photographic plates have been used to make holograms, and future work would be directed towards extending this work to the production of holographic lenses on large photographic plates. No real problems should be expected in this area.

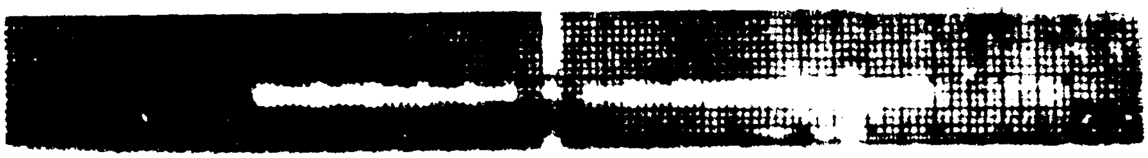


Figure 4.8. Photograph of Holographic Image P'_{2R} and Scanning Laser Probe Beam.

SECTION 5

GRID BOARD DIGITIZATION SYSTEM FOR EVALUATION OF GRID BOARD PHOTOGRAPHS

As part of this program it was required that a technique be proposed for quantifying the evaluation of optical distortion in aircraft windscreens. It was required that this technique be able to quantify the "binocular effects" as well as the conventional optical distortion effects. Although the two techniques described in section 4 could be used to obtain the quantified optical distortion data, they are still in a development stage.

Grid board photography is a technique widely used for windscreen evaluation, but it is now limited by the time required for the manual data evaluation and the accuracy of these results. To overcome these limitations it is proposed that a system be developed to evaluate grid board photographs with the required accuracy and within a reasonable time.

5.1 DESCRIPTION OF THE PROBLEM

Agreement can not be reached on a standard for evaluating optical distortion, because of the various effects associated with its presence. Optical distortion refers to the localized and overall variations in the image apart from the true images, and is caused by variations in thickness, wedge, or curvature of an optical windscreen. The rays of light traveling through such a windscreen are bent or deviated, both angularly and laterally, and to different degrees. These variations of deviations with changing line of sight can have severe effects on the appearance of objects viewed through the transparency. The resulting image can: (1) be bent out of shape; (2) appear magnified or demagnified due to optical power in the windscreen (lensing); (3) be magnified or demagnified in only one dimension, as well as be shifted in space, due to unequal curvatures of the transparency (anamorphic distortion); and (4) have small localized distortions

such as localized power errors (bulls' eyes) or symmetrically connected smaller areas (butterflies) due to irregularities or discontinuities in coatings on the transparency.

The effect of distortion of an image is primarily psychological; therefore, the precise accuracy of measuring distortion is difficult to specify. A localized distortion may appear less of a problem than a widespread distortion, since the mind can easily correct for a localized discrepancy. A widespread distortion will warp an image without presenting a known reference of what the object should look like or where it should be located. Therefore, a widespread distortion may give "false" information about the object being viewed. However, a sharp localized distortion may cause an image to jump or change in shape or size very quickly as the image traverses the field of view. This could be very disturbing and confusing, especially in a situation requiring a quick decision. It is clear that all distortion tests must ultimately relate to human factors. However, straightforward visual inspection requires experienced personnel and is very subjective.

To determine how an image is being degraded by optical distortion, any test method must evaluate the extent to which the light rays from a test object passing through the test transparency are deviated in the final image plane, and must map the deviation of the various rays from their paths for a "perfect" image. A number of techniques have been proposed to accomplish this, including direct point-by-point mappings using a laser beam or telescope system.

5.2 CURRENT EXPERIMENTAL TECHNIQUES

The most commonly used techniques for distortion testing involve photographing a grid board through the transparency being tested. These techniques include (1) taking a single exposure of the grid board and measuring the slope or magnification variations of any lines; (2) taking a double exposure, one

without the transparency in, and one with the transparency in, and looking for "splits" in the lines of the two exposures; (3) taking a triple exposure through the transparency, translating the transparency vertically between exposures, and measuring the "growth" of the grid squares; (4) taking a single exposure through a two-hole mask (a modification of number 3); (5) visually inspecting a grid pattern as seen through the transparency being tested.

The parameters measured by these photographic techniques are the same for the different approaches. A limitation to this is the manner in which the results are analyzed. These techniques do not directly measure absolute (total) or angular deviation. The lateral and angular deviation are coupled into one effect in these tests. It would be possible to determine the actual angular deviation to the undeviated beam by referencing the data found through the windscreen to the undeviated data and subtracting a calculated lateral displacement found by other means. Primarily these techniques measure the change of angular deviation. This is the major cause of any sudden changes in image figure, hence the distortion and lensing effect seen through the transparency. Since the grid board techniques are designed to test an entire area of the transparency at one time, these tests give an immediate indication of the overall distortion of the image caused by the transparency as it would be seen when in use. The direct analysis of the data received from the grid board photographing gives the point-by-point change in deviation.

5.3 CURRENT METHODS OF ANALYZING GRID BOARD PHOTOGRAPHS

An analysis of optical distortion of the transparencies is performed by several different techniques, most of which can be performed using a set of single exposure photographs. These photographs are taken at the left eye position, at the right eye position, at the design eye position, and without any

transparency inserted. The data from these photographs can then be compared to obtain binocular disparity, magnification, and other deviation information.

One measurement used in the evaluation of the F-111 transparencies is grid line slope, which gives an indication of the rate of change of the angular deviation. By comparing the size of the grid squares, seen through the transparency, to the size of the grid squares as seen with no transparency in place, a magnification or lens factor of specific areas of the transparency can be determined. Another measurement which can be made by referencing the distorted grid board photograph to the reference (undistorted) grid board photograph is the displacement of the grid lines. By measuring the maximum displacement of the horizontal and vertical grid lines, adding these numbers together, and multiplying by 1000, a quality factor of the transparency in terms of the "displacement grade" (as specified for the F-111 transparencies) can be determined. This measurement can be taken another step. If the reference and distorted grid board photographs are properly referenced to each other (so that there is an absolute grid line position correlation between them), the absolute grid line displacement caused by the windscreen can be determined. This displacement will contain information about both lateral displacement and angular deviation as caused by the windscreens. The lateral displacement caused by these windscreens is fairly constant and can be calculated either from the geometry and thickness of the windscreen or by taking another set of photographs with the grid board at a different distance from the windscreen as the first set and comparing the two sets. This lateral displacement can then be out from the data, yielding the angular deviation in minutes of arc. All of these numbers could prove invaluable in obtaining a complete quantitative picture of the optical quality of the transparencies.

5.3.1 Limits of the Accuracies

These measurements are limited by the accuracy of the measuring system used and the accuracy of the resulting statistical calculations. Currently, these measurements are made using a drafting table to measure distances and plot selected points. A trained individual could make these measurements fairly accurately. However, a trained and experienced person may also tend to make "rule of thumb" estimates to speed up this laborious task. In studies performed at the University of Dayton Research Institute using untrained personnel, an average error of 10 to 20 percent in measuring grid line slopes was found. To be meaningful, the displacement measurements must be made very accurately. In determining angular deviations caused by the transparencies, generally an accuracy of close to $\pm$ 1 minute of arc is required. To realize this accuracy on a photograph printed so as to have 16 grid squares per inch, the measurements must be made to an accuracy of less than 0.004 inches. This accuracy is very difficult to obtain repeatedly. Once this data is taken, it still must be analysed, preferably by computer. Each set of measurements opens up new possibilities for errors from either human factors (such as in transcribing and entering data) or accumulated errors from the measuring instruments.

Grid board photography is still a very useful technique. The experimental procedure for obtaining the photographs is simple, direct, and relatively inexpensive. By means of these photographs, an understandable, hard copy record of the optical quality of the windscreens (whatever the geometry) can be made and stored for future evaluation. Grid board photography has gained wide acceptance by the people involved in the manufacture and evaluation of windscreens. However, just visually inspecting the grid board photographs is very subjective and qualitative. The possibility of error in the quantitative analysis needs to be reduced along with the time and degree of experience required for the analysis.

Much of the problem of accuracy as well as the time and expertise required to obtain reliable quantitative results could be eliminated by the use of electronic digitization. The entire set of grid board photographs could be digitized easily and accurately by inexperienced personnel, using a digitizing tablet interfaced directly with a computer system. Such a digitizing tablet (and associated graphics tablet to print out the data again) is inexpensive, reliable, and accurate. Once the grid board photographs are digitized, the computer can be used to numerically compare the distorted grid board to the reference grid board or to a theoretical grid board (for the windscreen geometry) and to compare the grid board as seen from the left and right eye positions to obtain binocular disparity information. Grid line slope, line displacement, magnification, angular deviations, and overall quality factors can all be obtained directly from the computer without further "handling" of the data being necessary. This digitizing system can be small and durable so as to be easily adaptable to an on-site manufacturing situation.

5.4 PROPOSED SYSTEM

The system proposed to accomplish this digitization task consists of a digitizing tablet, a computer system (including terminal and memory capability), and a graphics tablet for printing out the original grid board data. The digitizing tablet must be durable, accurate, and versatile. Actual data acquisition is accomplished by means of a multi-button cursor and/or pen, enabling the input to the computer to be coded by type and nature of the input directly from the digitizing tablet. The accuracy of the coordinants input from the tablet is 0.01 inches or better with a high degree of repeatability possible. The computer needs to be a dedicated system, to prevent data from being rejected or lost (thus giving incorrect results), with internal memory of at least 16K along with disc and/or magnetic tape storage available for long-term storage capability (eliminating

the need to enter the data more than once). The graphics tablet will allow the stored digitized data to be printed back out. This will allow a check to be made of the digitized data by comparing the stored data to the original photograph. The digitized grid board data can also be added, subtracted, or otherwise modified by the computer and the resultant can then be printed out by means of the graphics tablet.

The general operation of this system will be simple yet versatile enough to allow for a variety of different possible outputs and calculations, with provisions built in to allow the program to be generic in nature with future modifications possible to fit users' needs. The system will directly take in x-y coordinant data from the digitizing tablet in a coded manner depending on the form and nature of the data. This input would be the coordinants of the intersection points of grid lines or whatever features are of interest. Not every point or area would need to be digitized. Points of interest could be digitized, leaving the other points to be interpolated by the computer.

The data can then be scaled, offset, or tilting as required by the software by inputting discrete and absolute reference points, which can be incorporated into each photograph. The computer can then either calculate or contain (in data files) the appropriate data relating to a perfect undistorted grid board and a theoretical grid board in accordance with the given transparency geometry. The input data can then be compared to either the calculated theoretical data or to other input data (such as comparing left and right eye position data).

From these point-by-point numerical comparisons the system can then either output a resultant grid board or the numerical information in the form of grid line slopes, line deviations, magnifications, and overall quality factors. Given the associated limiting values for these different quantities, the output could identify what conditions of optical quality were exceeded and in what areas. This could be done by identifying how many

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[illegible]	[illegible],[illegible]0.00
Graphics tablet -	[illegible],[illegible]00.00
Other related [illegible]	[illegible],[illegible]00.00
	[illegible],000.00

Some of this equipment [illegible] which would significantly reduce the cost. Approximately [illegible] months would be required to develop the [illegible] [illegible].

[illegible]	$55,000.00
Total	$[illegible]3,000.00

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